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ALLOY SYSTEMS FOR BRAZING OF COLUMBIUM AND TUNGSTEN

TECHNICAL DOCUMENTARY REPORT No. ASD-TR-61-592
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DIRECTORATE OF MATERIALS AND PROCESSES
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

PROJECT No. 7351, TASK No. 735101

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(Prepared under Contract No. AF 33(616)-7484
by General Electric Company, Evendale, Ohio;
W. R. Young, Author)

NOTICES

FOREWORD

This report was prepared by the Metallurgical Engineering Sub-Operation of the General Electric Company, Flight Propulsion Laboratory Department. The work was initiated by the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, under Contract AF 33(616)-7484, Task No. 73512, under the title of "Investigation Of The Physical Metallurgy Of Joining Of Columbium And Tungsten". Mr. J. T. Gow served as ASD Project Engineer.

This report covers work done from July 1, 1960 through August 31, 1961 on the brazing of Cb alloys and W. The results of the study of the physical metallurgy of tungsten welding are covered in a separate report.

The studies were conducted by the following General Electric personnel:

W. R. Young, Project Engineer

E. S. Jones, Project Manager

C. E. Shamblen and several other Metallurgical Engineering personnel contributed to the work. Dr. W. H. Chang reviewed the manuscript of the report and made helpful suggestions. Miss Dolores Kappes and Mrs. Leona Gilbert prepared the manuscript.

ABSTRACT

The purpose of this work was to gain sound metallurgical insight into the joining of tungsten and columbium alloys by brazing. Columbium alloys selected for study in this program were F-48 alloy (Cb + 15W + 5 Mo + 1Zr) for service to 2500°F, and Cb-1Zr alloy for service in the 1800 to 2200°F temperature range. High purity, powder metallurgy tungsten sheet was used for the tungsten brazing studies.

Brazing alloys were designed on the basis of compatibility with Cb and W, and melting temperatures. All brazing alloys were then evaluated for hardness, melting range, wettability and flow, and diffusion reactions with the base metals. Brazed panels were examined both as-brazed and after suitable diffusion treatments.

Based on results of this initial evaluation, four brazing alloys for use with columbium alloys were selected for further study. These alloys - AS-537 (Zr-28V-16Ti), AS-536 (Ti-6Fe-4Cr), AS-501 (Ti-30V), and AS-514 (V-35Cb) - exhibited useful brazed joint strength and had negligible effect on the ductile-to-brittle transition temperature of the base metals.

Brazing alloys showing best characteristics for use with unalloyed tungsten were AS-517 (Cb-2.2B) and AS-519 (Cb-20Ti). These alloys exhibited excellent wettability and flow, and negligible base metal erosion during brazing. Thermal exposure of brazed panels produced significant diffusion reactions that will require further study.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

I. PERLMUTTER
Chief, Physical Metallurgy Branch
Metals and Ceramics Laboratory

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1. INTRODUCTION

To produce results of maximum usefulness, a research program on the brazing of tungsten and columbium alloys must have both properly selected objectives and a logical plan of execution, based on sound metallurgical principles. The selection of objectives for this study was not a simple matter, as they should take into account the following factors:

1. Probable applications of tungsten and columbium alloys.
2. Temperature-time-stress requirements associated with these applications.
3. Anticipated chemical environments.
4. Mechanical properties of the base metals and alloys.
5. Recrystallization temperatures of the two metals and their alloys.

Since many of the factors regarding applications are to a great extent unpredictable, objectives cannot be set with great precision. However, reasonable assumptions regarding these applications can be made. Combining these assumptions with known facts regarding the metals and their alloys leads to the following analysis which can furnish the basis for selecting program objectives:

1. Potential applications for tungsten, and eventually its alloys, include:
   a) Solid propellant rocket engine hot parts.
   b) Structural components of advanced flight systems (i.e. reentry vehicles, etc.).

2. Typical requirements for tungsten applications are:
   a) Up to 6000°F - 10 minutes - low stress.
   b) 2500 to 3500°F - 10 hours - low to moderate stress.

3. Potential applications for columbium and its alloys include:
   a) Structural components of advanced flight systems (i.e. reentry vehicles, space power systems, hypersonic ramjets, etc.).
   b) Heat exchangers for high temperature nuclear reactors.

4. Typical requirements for columbium applications are:
   a) 2500 to 2600°F - 10 minutes - moderate to high stress.
   b) 2000 to 2500°F - 10 hours - moderate to high stress.
   c) 2000°F - 10,000 hours - low to moderate stress.

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The above by no means represents all of the possible requirements which tungsten and columbium alloys might encounter, but they serve to show that alloys of varying strength capabilities can be used to meet specific requirements.

5. Unalloyed tungsten possesses no strength advantage over other refractory metals and alloys below about 2500 to 2600°F. No high strength tungsten alloys are currently available.

6. Unalloyed columbium is relatively weak, but columbium alloys with varying useful strength capabilities are available.

7. Low strength columbium alloys recrystallize at about 2100 to 2200°F in one hour; at least one high strength alloy recrystallizes at about 2800°F in one hour. Wrought tungsten recrystallizes in the range 2500 to 3000°F (one hour).

The following conclusions can be drawn from the foregoing analysis:

1. There are very few potential applications for tungsten below its recrystallization temperature. Therefore, arbitrarily, the brazing alloy studies should initially determine braze/base metal interactions at temperatures in the general range between 2500 and 3500°F. In these studies, recrystallization of the tungsten is likely to occur during brazing. It would, however, be desirable to maintain a wrought condition in brazed structures to facilitate mechanical handling, and possibly for improved thermal shock resistance. Recrystallization may hopefully be avoided by the development of high remelt temperature brazing alloys, or by tungsten alloys which recrystallize above the brazing temperatures.

2. Two distinct types of applications for columbium alloys can be identified. One type involves low strength alloys for use where stresses are quite low (e. g. heat exchangers), or where design techniques, such as use of honeycomb sandwich construction, can be employed to enhance the basic strength capabilities of an alloy. Brazing temperatures will probably exceed the recrystallization temperatures of the low strength alloys, but this should be tolerable since these alloys retain room temperature ductility in the recrystallized condition.

The second type of application - for higher temperature, higher stress - will involve the highest strength columbium alloys. Since F-48 (the strongest columbium alloy now in pilot production) recrystallizes above 2500°F and is not embrittled by recrystallization up to at least 2800°F, it should be possible to braze it for 2500°F service without loss of ductility. Furthermore, it has been shown that recrystallized F-48 loses only a small portion of its unrecrystallized strength in the 2000 to 2500°F region.

In terms of likely service requirements then, the objectives of these brazing studies are the development and evaluation of brazing alloys and techniques for:

1. Unalloyed tungsten for short time, low to moderate stress service at 2500 to 3500°F.

2. A columbium alloy for short time, high stress, or longer time, lower stress, service to 2500°F.

3. A columbium alloy for long time, low to moderate stress service at 1800 to 2200°F.

2. BRAZING ALLOYS FOR COLUMBIUM

2.1 BACKGROUND

Brazing may be defined simply as a joining process wherein a suitable filler metal is melted, distributed in the joint by capillary attraction, and solidified upon cooling. The filler metal must melt above the service temperature, but below the melting point of the metals to be joined. From a practical viewpoint, the braze filler and base metal should be compatible in metallurgical and physical properties to prevent interactions which may destroy or minimize the effectiveness of the brazed joint.

The principal considerations in the design of brazing alloys are, therefore, melting range and compatibility with base metals. The evaluation of joints produced by these alloys also includes wettability and flow, braze integrity, joint mechanical properties, and the effects of brazing thermal cycles on parent metal properties. In the case of refractory metal brazing, the evaluation of compatibility between brazing alloys and protective coatings should also be included.

To aid in brazing alloy design, literature searches on "refractory alloy brazing", and on "binary and ternary phase relationships of columbium, tungsten, and appropriate compatible elements (Mo, Ti, Zr, Hf, V)" were initiated with the ASM Documentation Service and the FPD Technical Information Center.

The search on "binary and ternary phase relationships with Cb, Mo, W, V, Ti, Zr, or Hf as one constituent" produced fruitful results, references obtained being useful in the study and design of brazing alloy systems. For example, a recent investigation of the zirconium-silver binary system (1) placed the eutectic composition at 42 weight % Ag, as compared to the previously reported 12 weight % Ag. Thus, silver was not considered to be a good potential temperature depressant for zirconium and this binary system was deleted.

Also, a comprehensive investigation of the Ti-V-Zr ternary system (2) indicated that formation of the ZrV_2 intermetallic phase in the Zr-V binary system could be suppressed by addition of titanium. Since the low melting eutectic (2250°F) of the Zr-V system could be retained, this ternary system offered an excellent combination of low melting point plus good compatibility with columbium.

All available binary phase relationships for columbium were tabulated and are presented in Table I (3-6). This table shows solubilities, low melting phases, and intermetallic compounds. It is evident that columbium alloys containing tungsten, molybdenum, tantalum, vanadium, titanium, zirconium, and hafnium exhibit no intermetallic phases or eutectic formation.

2.2 BRAZING ALLOY DESIGN

The goals proposed for columbium brazing alloy studies are (1) to develop brazing alloys for service to 2500°F, and (2) to develop brazing alloys for service at 1800 to 2200°F.

2.2.1 Requirements

2.2.1.1 Goal One - Service To 2500°F

Solidus temperature of the brazing alloy should be in the range 2700 to 3100°F. The liquidus temperature should be no more than 200°F above the solidus (2900 to 3300°F) to avoid liquation during the brazing cycle.

TABLE I - SURVEY OF COLUMBIUM BINARY ALLOY SYSTEMS

System	Wt. % Soluble X in Cb	Wt. % Soluble Cb in X	Low Melting Phases °F	Known Sigma Phase	Known Intermetallics	Reference
Cb-Al	?	?	?	None	$CbAl_3$(53.44 Cb) $CbAl_2$	(1)
Cb-Au	?	?	?	None	Cb_3-Au Cb-Au_2	(2)
Cb-B	?	?	Yes	None	Cb-B (10.43 B) Cb_3-B_4 (13.44 B) Cb-B_2 (18.89 B) Cb_3-B (3.74 B) Cb_2-B (5.50 B)	(1, 3)
Cb-Be	?	?	?	None	Probable	(1)
Cb-C	0.0025	0	?	None	Cb-C (11.45 C) Cb_2-C (25.9-33.3 C)	(1)
Cb-Co	$\angle$6.6	4 @ 1886°F $<$3 @ R.T.	Eut. -Co-Cb-Co_2 (21Cb)-2255°F	None	Cb-Co_2	(1, 2)
Cb-Cr	12.3@3020°F 7.4@2730°F	17.3 @ 2910°F 7.4 @ 2730°F 6.4 @ 2550°F	Eut.-Cr-$CbCr_2$ 32.9Cb-2910°F $CbCr_2$-Cb 53.3 Cb-3020°F	None	Cb-Cr_2(47.3Cr)	(4)
Cb-Cu	$\sim$2.05	.4	None (Probably simple peritectic)	None	None	(3)
Cb-Fe	$\sim$2.4@ 3000°F decreasing to small solubility at R.T.	α- iron $<$.36@ R.T. 1.8@ 1812°F γ - iron 1.1@ 1812°F 2.0@ 2228°F	Eut. 18Cb-2480°F 67Cb-2840°F 73Cb-2759°F(?)	Yes	Cb-Fe_2, Fe_2Cb_3	(3)

(continued)

TABLE I (continued)

System	Wt. % Soluble X in Cb	Wt. % Soluble Cb in X	Low Melting Phases °F	Known Sigma Phase	Known Intermetallics	Reference
Cb-Ge	?	?	Probable	None	$Cb-Ge_2$(60.98 Ge) Cb_2-Ge Cb_3-Ge_2 Cb-Ge Cb_3-Ge	(1)
Cb-Hf	Probably 100% above transformation temp. of Hf. 82(1832°F)		None	None	None	(1)
Cb-Mn	?	?	?	None	$Cb-Mn_2$(45.82 Cb)	(1)
Cb-Mo	100	100	None	None	None	(1)
Cb-Ni	<5	20.5(2318°F) 10.0(1652°F)	Eut. 2318 (23.5 Cb) 2147 (51.6 Cb)	Yes ~34 Ni	$Cb-Ni_3$ Cb-Ni (?)	(1, 2)
Cb-Os	~13.3(max)	~5(max)	?	Yes (57.7 Os)	Cb_3-Os $Cb-Os_2$	(2)
Cb-Pd	~8.3(max)	~9.3(max)	?	Yes (42.5 Pd)	$Cb-Pd_3$	(2)
Cb-Pt	~13.7(max)	~7.8(max)	?	Yes (55.8 Pt)	Cb_3-Pt $Cb-Pt_3$	(2)
Cb-Re	62.1(max) ~40@1332°F	<1.0(max)	?	Yes (66.73 Re)	Chi (76.6-92.5 Re)	(3)
Cb-Rh	~8.8(max)	~23.2(max)	?	Yes (~37 Rh)	Cb_3Rh(26.97 Rh) Probably two other compounds.	(2)
Cb-Ru	~42.2(max)	~28.1(max)	?	Probable ~50 Ru	Probable (60.2-69.9 Ru)	(2)
Cb-Si	<1.6	0	Eut. 3416(~6.2Si) 3362(29.5Si) 2561(92Si)	None	Cb_4Si Cb_5Si_3 $Cb-Si_2$	(1)

(continued)

TABLE I (continued)

System	Wt. % Soluble X in Cb	Wt. % Soluble Cb in X	Low Melting Phases °F	Known Sigma Phase	Known Intermetallics	Reference
Cb-Ta	100	100	None	None	None	(1)
Cb-Th	Negligible	$<$0.1 in α Th $<$ 1.0 in β Th	Eut. 2615°F(8 Cb)	None	None	(1
Cb-Ti	100 Beta β / α + β boundary for 1625, 1562, 1472, and 1382 lies at 0, 3.5, 10.5 and 20 percent Cb respectively.	100 Beta 3@1112°F-Alpha	None	None	None	(1)
Cb-V	100	100	None	None	None	(3)
Cb-W	100	100	None	None	None	(1)
Cb-Zr	100 Beta Eutectoid occurs at $\sim$1085°F with 13% Cb. Between $\sim$13 and $\sim$87% Cb, Alloys decompose into two solid solutions below 1832°F.	100 Beta	Min. 3164(22Cb)	None	None	(3)

REFERENCES

1. Hansen, M. "Constitution of Binary Alloys", 2nd Ed. McGraw-Hill, New York, 1958.

2. Dwight, A.E., "Alloying Behavior of Columbium". Columbium Metallurgical Symposium of AIME, Lake George, New York, 1960.

3. Miller, G. L., "Metallurgy and the Rarer Metals No. 6, Tantalum and Niobium" Academic Press Inc., New York, 1959.

4. Elyutrn, V. P. and Funke, V. F. "Some Data on the Phase Diagram of the Chromium-Columbium System", Izuestiya Akad, Navk SSSR, Otdel, Tech., Nauk, March 1956. (Brutcher Translation # 4304, 1958).

The brazing alloy should be compatible with Cb, i.e., no brittle intermetallic compounds or low melting phases ($<$ 2700°F) should be formed during brazing or subsequent service.

Brazed joints should possess useful ductility from room temperature to the service temperature.

The brazing alloy coefficient of thermal expansion should be similar to that of the base alloys.

The brazing alloy should have useful strength at 2500°F.

2.2.1.2 Goal Two - Service At 1800 to 2200°F

The requirements are the same as those for Goal One with the exception of brazing alloy solidus and liquidus temperatures. In this case, the solidus temperature should be in the range 2000 to 2800°F, i.e., 200°F above the minimum service temperature to 600°F above the maximum (2200°F) service temperature. Liquidus temperature should thus be in the range 2200 to 3000°F. No low melting phases ($<$ 2000 to 2200°F) should be formed during brazing or subsequent service.

Obviously, many potential brazing alloys will not meet all these requirements; however, they serve as a general guide for the selection of brazing alloy systems.

2.2.2 Considerations

The survey of columbium binary alloys showed that Mo, Ta, W, V, Hf, Ti, and Zr form no intermetallic compounds when alloyed with Cb. Eutectic phases which melt below 2500°F are formed in Cb binary alloys with Fe, Ni, and Co.

In the design of brazing alloys for columbium, two approaches become evident. First, the refractory metals Mo, Ta, W, and Cb itself may be considered as base metals. One difficulty with this approach is the high melting point of these elements. Suitable alloying additions must be made which will lower the liquidus temperature of binary alloys into the proposed brazing temperature range. Secondly, lower melting point elements which are compatible with Cb (i.e., V, Hf, Ti, and Zr) may be considered as base metals for brazing alloys. Some brazing alloys based on Ti and Zr have been evaluated for compatibility with Cb, but no mechanical property data was determined.

2.2.3 Brazing Alloy Selection

2.2.3.1 Goal One - Service To 2500°F

In selecting the first requirement for the brazing alloys, a liquidus temperature within the range 2900 to 3300°F was considered necessary for unalloyed elements and binary alloy systems of the elements compatible with columbium. For simplicity, the compatible elements were divided into two classes: (1) the relatively low melting elements - Ti, Zr, Hf, and V, and (2) the refractory metals - Ta, Mo, W, and Cb itself. Binary alloys with liquidus temperature within the range 2900 to 3300°F are listed below for each class of compatible elements and all combinations thereof.

Group 1 - Unalloyed Metals Compatible with Cb:

Ti - melting point, 3128°F

Group 2 - Unalloyed Metals Incompatible with Cb:

Pt - melting point, 3218°F

Group 3 - Alloys of the Low Melting Compatible Elements, Ti, Zr, V, and Hf

In this group, Hf alloys will not be considered since there is only scant information available on binary alloys. (Also, the properties of Hf alloys should be similar to Zr binary alloys.)

Binary alloys with suitable liquidus temperatures are:

Ti - V - minimum 2950°F at 30% V

Ti - Zr - minimum 2930°F at 50% Zr

Zr - V - eutectic 2240°F at 30% V, (ZrV_2 at 48% Zr)

Group 4 - Alloys of the High Melting Compatible Elements, Ta, Mo, W, and Cb

No alloys in this group have liquidus temperatures within the 2900 to 3300°F range.

Group 5 - Alloys by Combination of Compatible Elements in Groups 3 and 4

Only binary alloys which do not form intermetallic compounds are considered:

Ta - Zr - eutectic 49.5% Zr at 2885°F

Cb - V - minimum 3290°F at 65% V

Cb - Zr - minimum 3165°F at 78% Zr

Group 6 - Alloys by Combination of Refractory Metals (Group 4) and Elements Incompatible with Columbium

In this group, only alloys with less than 50 weight percent incompatible element were considered. No binary alloys of molybdenum and tungsten have liquidus temperatures below 3300°F with less than 50% alloy element.

Cb - B - eutectic 2.2% B - 2930°F (CbB, CbB_2, etc.)

Cb - Co - eutectic probable - ($CbCo_2$)

Cb - Cr - eutectic 46.7% Cr - 3020°F - ($CbCr_2$)

Cb - Fe - eutectic 17% Fe - 2760°F - ($CbFe_2$)

Cb - Ni - eutectic probable - (CbNi, $CbNi_3$)

Ta - Fe - eutectic 20% Fe - 3000°F - ($TaFe_2$)

Based on the above considerations of solidus and liquidus temperatures and compatibility with Cb, five binary alloy systems were selected for study as shown in Table II. For comparison with compatible alloys, one alloy system (Cb-B) was selected in which B forms intermediate phases with Cb.

TABLE II

BRAZING ALLOYS FOR SERVICE WITH F-48

Alloy Designation	Nominal Composition Wt. %	Expected Melting Range, °F Solidus	Liquidus
AS-500	100 Ti	3130	3130
AS-513	V - 20 Ti	3180	3280
AS-501	Ti - 30 V	2950	2950
AS-509	Zr - 22 Cb	3165	3165
AS-514	V - 35 Cb	3290	3290
AS-516	Cb - 1.0 B	-	-
AS-517	Cb - 2.2 B	2930	2930
AS-539	Cb - 3.0 B	-	-
AS-525	Ta - 49.5 Zr	2885	2885
AS-538	Zr - 34 Ta	-	-

2.2.3.2 Goal Two - 1800 To 2200°F Service

The binary alloy systems which are compatible with columbium have been previously described in the consideration for application to 2500°F (Goal One). In order to attain the solidus and liquidus temperatures thought necessary for 1800 to 2200°F service, brazing alloys which contain alloying elements not compatible with columbium must be considered.

The known melting points of binary alloys of V, Ti, and Zr are shown in Table III. It is apparent that a large number of these binary alloys have a liquidus temperature within the 2200 to 3000°F temperature range required. Five binary alloys have been selected for study from this group for potential service to 2200°F on columbium alloys as shown in Table IV.

TABLE III

SOLIDUS AND LIQUIDUS TEMPERATURES OF BINARY ALLOYS OF TI, ZR, AND V

Alloying Elements, Wt./% Melting Points * °F	Alloying Elements	5% Sol.	5% Liq.	10% Sol.	10% Liq.	15% Sol.	15% Liq.	20% Sol.	20% Liq.	Eutectic % Wt./%	Eutectic % Temp. °F
Titanium											
3128	Ag	3070	3090	2980	3050	2860	2980	2710	2920	--	--
3128	Al	3080	3090	3020	3050	2950	2980	2900	2930	--	--
3020	Co	2400	2800	2010	2550	1880	2300	1880	2140	28	1880
3020	Cu	2730	2890	2350	2770	1880	2620	1810	2490	--	--
3128	Cr	3020	3060	2910	2980	2790	2880	2710	2800	--	--
3020	Fe	2680	2780	2390	2600	2200	2420	2060	2280	32	1980
3020	Mn	2880	2940	2710	2860	2580	2760	2440	2670	43	2150
3128	Ni	2760	2980	2000	2760	1720	2520	1720	2300	28	1720
Zirconium											
3380	Ag	2480	3020	2280	2480	2280	2340	2280	2400	12	2280
3380	Al	2880	3000	2460	2560	--	--	--	--	11	2460
3360	Cr	2360	3080	2360	2800	2360	2520	2360	2420	18	2360
3380	Cu	1820	3120	1820	2540	1820	2200	1820	1920	22	1820
3380	Fe	1710	3020	1710	2340	1710	1760	1710	2000	16	1710
3360	Ge	2790	3020	2790	2820	--	--	--	--	8	2790
3380	Mn	2240	3100	2080	2720	2080	2400	2080	2190	22	2080
3380	Ni	1760	3000	1760	2370	1760	1840	1760	2040	17	1760
3360	Be	--	--	--	--	--	--	--	--	5.5	1796
Vanadium											
3430	Al	3410	3430	3380	3420	3340	3410	3300	3400	--	--
3430	Co	3260	3300	3040	3160	2860	3040	2700	2940	--	--
3430	Fe	3330	3350	3230	3280	3130	3190	3050	3120	--	--
3420	Ni	--	3340	--	3240	--	3100	2320	2980	--	--
	Be	--	--	--	--	--	--	--	--	15	3000

* Melting points of base metals used for phase diagram determination, variation due to differences in impurity content.

TABLE IV

BRAZING ALLOYS FOR SERVICE WITH Cb-1Zr

Alloy Designation	Nominal Composition Wt. %	Expected Melting Range, °F Solidus	Liquidus
AS-502	Ti - 5 Fe	2680	2780
AS-503	Ti - 10 Fe	2390	2600
AS-504	Ti - 20 Fe	2060	2280
AS-505	Ti - 10 Cr	2910	2980
AS-506	Ti - 20 Cr	2710	2800
AS-507	Ti - 2 Be	-	2730
AS-510	Zr - 12 Ag	2280	2280
AS-511	Zr - 11 Al	2460	2460
AS-535	Ti - 13 Fe - 8 Cr	-	-
AS-536	Ti - 6 Fe - 4 Cr	-	-
AS-537	Zr - 28 V - 16 Ti	-	-

2.3 EXPERIMENTAL PROCEDURE

Alloys selected for evaluation were based on the Ti, V, Zr, Cb, and Ta binary systems. Since the mechanical properties of these metals are influenced significantly by their interstitial content, purity of starting materials and melting procedures were carefully controlled to minimize contamination which could result in embrittlement of the arc melted button heats.

2.3.1 Preparation Of Alloys

Alloys were prepared for melting point determination and compatibility studies by conventional non-consumable, tungsten electrode arc-melting. The melting charges were weighed (30 gm), cold pressed, and placed in water-cooled copper crucibles in the arc furnace. The furnace chamber was evacuated to less than 1×10^{-4} mm Hg, and back-filled with high purity helium. All alloys were melted two or more times to insure homogeneity.

Since the dependency of hardness on purity is marked, hardness can be used as a measure of the purity of these base metals. Therefore, button heats of each base metal were melted and their hardnesses compared with values from the literature. In this way, acceptable standards of starting material purity and melting procedure were established. The as-cast hardness of the unalloyed base metals are shown in Table V. The hardnesses of the first alloys of vanadium and tantalum were above acceptable limits. These base metals were subsequently re-melted using higher purity materials. As expected, a considerable reduction in as-cast hardness was achieved. For vanadium, the hardness decreased from 455 VHN to 147 VHN. Similarly, the tantalum hardness decreased from 342 VHN to 109 VHN.

Brazing alloys which were brittle were crushed mechanically to obtain powders suitable for brazing studies. The ductile alloys were machined to chips. Alloy contamination was avoided during machining by eliminating coolants, using conditions which minimized chip heat-up, and catching the chips on aluminum foil.

2.3.2 Preparation Of Brazed Specimens

The columbium alloys selected for this program were the F-48 (Cb - 15 W - 5 Mo - 1 Zr) for service to 2500°F, and the Cb-1Zr alloy for service in the 1800 to 2200°F temperature range. The Cb-1Zr alloy was utilized in the as-rolled condition. The F-48 alloy was stress-relieved at 2200°F/1 hr. prior to brazing studies. The analyses of the ingots for interstitial elements are shown in Table VI.

TABLE V **CHEMICAL ANALYSIS AND HARDNESS OF ALLOYING ELEMENTS USED IN BUTTON HEATS**

Element	Form	Lot	Vendor	Chemical Analysis, w/o O	N	H	C	Other	As-Cast Hardness VHN	Ductility[1]
Titanium	Powder -20 +100 mesh	4725	Union Carbide	.07	.01	.007	.02	(.12Fe, 12Cl)	120,130,137	Ductile
Zirconium	Platelets	--	U.S.I.	.14	.005	.005	.05	(99.6Zr)	173	Ductile
Vanadium	Powder -100 Mesh	RB135	City Chem.	.21	--	.002	.028	(.026Fe)	455	Brittle
Vanadium[2]	¼ + 20 Mesh	36889	Union Carbide	.04	.039	.002	.023		147	Ductile
Columbium	Roundels	BM461	Union Carbide	.06	.007	--	.003		132	Ductile
Tantalum	Powder -200 mesh	Mo#3	Kennametal	.09	.016	--	.020	.01Cb, .02Si .003Ti, .02Fe 99.81 Ta	342	Ductile
Tantalum[2]	.045" Rod		Ametco	.002	.003			99.9 Ta	109	Ductile
Molybdenum	Powder	4675	Metals and Residues	.025	.004	--	.003	(99.94 Mo)	181	Brittle
Nickel	Electro-lytic Platelets	--	Inter. Nickel	(99.95Ni, .01-.04Fe, .01-.03Co)					--	--
Iron	"	A-101	Plastic Metals	.070	--	--	.018	.002Mn, .005S .002Cr, .99.84Fe	--	--
Chromium	Powder	107	Lunex	.02	.0005	.0005	.018	(99.8Cr)	--	--
Aluminum	Shot	Wo67	Alcoa	(.13Fe, .08Si, .01Ni, .01Ti, .01V, 99.76Al)					--	--
Palladium	Powder -50 Mesh	--	J. Bishop	(99.90Pd)					--	--

1) As determined by "hammer and chisel" test. 2) Starting materials used for brazing alloys reported.

TABLE VI

INTERSTITIAL ELEMENT CONTENT OF BASE ALLOYS

Alloy	Heat Number	Chemical Analysis - ppm			
		C	O	N	H
Cb-1Zr	1012-741 Wah Chang	30	285	85	1.6
F-48	W-14 General Electric	170	430	70	-

The base metals were cut into 1" X 1" panels, degreased with acetone, and etched to remove surface contamination. A fixed volume of brazing alloy, 0.15 cc, was then placed on the panel. The alloy was applied directly from glass storage vials to prevent handling of either the brazing alloy or the base metal.

Brazing alloys were evaluated for melting range in a resistance heated, vacuum furnace capable of operation to 4500°F. During brazing, the vacuum was maintained at 10^{-4} mm Hg or better. As an added precaution against contamination, panels were placed inside a tantalum container.

To determine the approximate melting range, alloys were observed directly with a micro-optical pyrometer. Although this procedure was useful for rough melting point determinations, it was subject to errors in temperature measurement. These errors were caused by inability to detect initiation of melting optically, non-black-body conditions, and thermal transients which occurred as the temperature was continually increased. Therefore, final determinations of braze alloy melting range were made by heating to a pre-determined temperature which was maintained for five minutes. Temperatures were determined using a micro-optical pyrometer which was sighted on a 30° tantalum cone to insure black-body conditions. This pyrometer was frequently calibrated by comparison with a thermocouple attached to the panel being brazed. Standard calibration techniques were employed to insure pyrometer accuracy at temperatures above the thermocouple range.

Using this procedure, four braze alloys could be evaluated during each furnace cycle, thus allowing a comparison of flow characteristics at a given temperature. The pre-determined temperatures were varied at first 100°F,

then $50^{o}F$ intervals until the complete melting range of the braze alloys was established.

2.3.3 Metallographic Studies

After brazing, metallographic specimens were prepared and the microstructure, depth of parent metal solutioning, braze contact angle, and hardness traverse were determined for each brazed panel.

The procedure for preparation of metallographic specimens proved to be troublesome due to excessive reaction of Cb etching solutions with the braze alloy. In some cases, complete erosion of the braze alloy would occur during the required etching time for the Cb-base alloy. To alleviate this situation, a double etching procedure was developed wherein one-half the specimen was protected by a plastic coating during etching of the Cb-base alloy. The protective layer was then stripped from the specimen and the braze alloy etched. Utilizing this procedure, one photomicrograph was obtained showing both the braze and base alloys with suitable etching conditions.

2.4 RESULTS AND DISCUSSION

2.4.1 Melting Range Determinations

The melting range determinations are summarized in Table VII. Two alloys, AS-507 (98Ti-2Be) and AS-510 (88Zr-12Ag) were not investigated. The AS-510 alloy was dropped when the eutectic in the binary system was found to occur at 42 w/o, as compared to the previously reported 12 w/o Ag. The systems Ti-Be and Zr-Be had been previously investigated by Oak Ridge National Laboratory personnel [7]. To avoid repetition, alloy AS-507 was dropped.

The brazing alloys which exhibited melting ranges significantly higher than predicted on the basis of phase equilibrium diagrams are denoted by an asterisk in Table VII. For the Ta-Zr system, AS-535 (Ta-49.5Zr) and AS-538 (Zr-34Ta), Wulff and Brophy [8] suggest that a eutectic reaction occurs at approximately $3320^{o}F$, and 51 w/o Ta. This eutectic temperature is about $435^{o}F$ higher than previously reported [9] and compares more favorably with results of our investigation. However, discrepancies in both melting range and eutectic composition were evident in this system.

TABLE VII

SUMMARY OF MELTING RANGE DETERMINATIONS (**)

Alloy	Nominal Composition Wt. %	Base Metal	Brazing Alloys For Columbium			Ductility
			Melting Range, ^{o}F		As Cast Hardness VHN	
			Expected	Actual		
AS500	100 Ti	F-48	3128 Sol. 3128 Liq.	3115 Sol. 3115 Liq.	130	Ductile
AS501	70 Ti -30 V	F-48	2950 2950	2970 2970	229	Ductile
AS509	78 Zr -22 Cb	F-48	3164 3164	3150 3190	223	Ductile
AS513	80 V -20 Ti	F-48	3180 3280	<3150 3190	231	Ductile
AS514*	65 V -35 Cb	F-48	3290 3290	3300 3400	332	Ductile
AS516	99 Cb -1.0 B	F-48	?	above 3400	232	Ductile
AS517*	97.8 Cb - 2.2 B	F-48	2930	above 3400	301	Ductile
AS525	50.5 Ta 49.5 Zr	F-48	2885	<3400 >3400	-	Slightly Ductile
AS538	66 Zr - 34 Ta	F-48	?	<3000 3400	406	Brittle

(cont.)

TABLE VII (cont.)

Alloy	Nominal Composition Wt. %	Base Metal	Brazing Alloys For Columbium: Melting Range, °F Expected	Actual	As Cast Hardness VHN	Ductility
AS502	95 Ti -5 Fe	Cb-1.0 Zr	2680 2780	>2725 <2850	366	Ductile
AS503	90 Ti -10 Fe	Cb-1.0 Zr	2390 2600	- <2725	348	Ductile
AS504	80 Ti -20 Fe	Cb-1.0 Zr	2060 2280	<2100 2200	499	Brittle
AS505	90 Ti -10 Cr	Cb-1.0 Zr	2910 2980	>2850 <2980	299	Ductile
AS506	80 Ti -20 Cr	Cb-1.0 Zr	2710 2800	<2725 <2850	308	Ductile
AS507	98 Ti -2 Be	not investigated - see text				
AS510	88 Zr -12 Ag	not investigated - see text				
AS511	89 Zr -11 Al	Cb-1.0 Zr	2460 2460	>2400 <2500	494	Brittle
AS535	79 Ti -13 Fe -8 Cr	Cb-1.0 Zr	- -	<2400 <2500	412	Slightly Ductile

(cont.)

TABLE VII (cont.)

Brazing Alloys For Columbium

Alloy	Nominal Composition Wt. %	Base Metal	Melting Range, °F Expected	Melting Range, °F Actual	As Cast Hardness VHN	Ductility
AS536	90 Ti -6 Fe -4 Cr	Cb-1.0 Zr	- -	< 2725 < 2850	325	Ductile
AS537	56 Zr -28 V -16 Ti	Cb-1.0 Zr	- -	>2100 <2200	391	Ductile

* Alloys with melting range higher than expected.

** Time at melting temperature - 5 minutes

Vacuum 1×10^{-4} mm Hg

Brazing alloys from the binary system Cb-B had a eutectic network in the as-cast condition. However, melting was not observed at 3560°F, 630°F above the reported eutectic temperature for this system. Since the melting range was considered to be too high for use with F-48 alloy, additional tests were conducted on W panels. Results are reported in the section on "Brazing Alloys For W".

The anomalous melting temperatures indicated for the Cb-B and Ta-Zr systems, and less significantly for the Cb-V system, indicate the degree of uncertainty in existing phase equilibrium diagrams. These uncertainties may result from differences in starting materials, melting procedure, or evaluation techniques. Unfortunately, further exploration of these systems was beyond the scope of the present study.

With the above exceptions, the brazing alloys melted as expected. Brazed panels obtained from these melting point determinations were used to study the diffusion compatibility of brazing alloy systems with the base columbium alloys.

2.4.2 Metallographic Studies

The alloy wettability was excellent for all the brazing alloys tested, with contact angles ranging from 33 to 5 degrees at the melting point. Further increase in brazing temperature generally resulted in increased wettability, i.e., the contact angle for alloy AS-537 on Cb-1.0Zr (Appendix A, page IX) decreased from 29 to 11 degrees as brazing temperature was increased from 2200 to 2500°F. Also, it was noted that alloys with the highest contact angles (such as AS-536 and AS-501 with contact angles of 28° and 30°, respectively) exhibited excellent flow during brazing of capillary lap joints.

Some alloying between the brazing alloys and base alloys is essential to produce a metallurgical bond. In most cases, only minor alloying occurred during the five minute brazing cycle at the liquidus temperatures (Tables VIII and IX). The only brazing alloys which alloyed to a depth of .004" or greater were Ti-10 or 20% Cr on Cb-1.0Zr, and Zr-22 Cb and Zr-34 Ta on F-48. Unalloyed zirconium, which alloyed extensively with the F-48 base alloy, is included for comparison.

The extent of inter-diffusion between the brazing alloys and base metals was shown more clearly by metallographic examination and hardness traverses of the brazed panels. The type of specimen used for hardness determination is shown schematically below:

Table VIII - BRAZE ALLOY SELECTION CRITERIA

Base Alloy: Cb-1.0Zr For Service @1800 to 2200°F

Criteria	Property Requirement	Braze Alloy AS502 Ti-5Fe	AS503 Ti-10Fe	AS504 Ti-20Fe	AS505 Ti-10Cr	AS506 Ti-20Cr	AS511 Zr-11Al	AS535 Ti-13Fe-8Cr	AS536 Ti-6Fe-4Cr	AS537 Zr-28V-16Ti
Melting Range:										
-Solidus	2000-2800°F	>2725	-	<2100	>2850	<2725	>2400	<2400	<2725	>2100
-Liquidus (within 200°F of solidus)	2200-3000°F	<2850	<2725	2200	<2980	<2850	<2500	<2500	<2850	<2200
Wettability:	Contact Angle	22°	17°	5°	31°	30-18°	9°	12°	28-17°	11°
Compatibility:										
-Base Metal Erosion	<.002"	.002"	.001"	None	.004"	.008"	.002"	None	.002"	None
-Diffusion Reactions	Minimum	Grain Growth	Slight Grain Growth	None	Grain Growth	Grain Growth	None	None	Grain Growth	None
Ductility	Ductile	Ductile	Ductile	Brittle	Ductile	Ductile	Brittle	Slightly Ductile	Ductile	Ductile
Hardness: As Cast	<400 VHN	366	348	499	299	308	494	412	325	391
Hardness: As Brazed	-	270	350	500	250-300	270	550	400	300	380
Hardness: Heat Treated 2200°F/65 hrs.		280-400	320-378	530 (1800F)	300-450	280	-	360-450	300-340	350 (1800F)
Phase Transformations	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

Alloys Selected for Cb-1.0Zr

1800°F Service: AS537 (Zr-28V-16Ti) - Ductile, excellent compatibility with Cb, good potential for growth to higher melting point alloys.

2200°F Service: AS536 (Ti-6Fe-4Cr) - Representative of brazing alloys containing elements non-compatible with Cb. Ductile, negligible change in hardness upon heat treatment. Valuable in determining effect of grain growth in base alloys.

Table IX - BRAZE ALLOY SELECTION CRITERIA

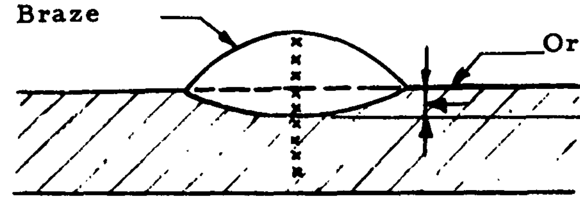
Base Alloy: F-48 For Service to 2500°F

Criteria	Property Requirement	Braze Alloy AS500 Ti	AS501 Ti-30V	AS508 Zr	AS509 Zr-22Cb	AS513 V-20Ti	AS514 V-35Cb	AS538 Zr-34Ta
Melting Range:								
Solidus	2700 - 3100°F	3115	2970	3320	3150	< 3150	3300	3000
Liquidus	2900 - 3300°F	3115	2970	3330	3190	3190	3400	3400
(within 200°F of solidus)								
Wettability:	Contact Angle	41°	33°	20°	27°	8°	12°	17°
Compatibility:								
-Base Metal Erosion	< .002"	.003"	.002"	.019"	.004"	.003"	.001"	.006"
-Diffusion	Minimum	.008" diff. layer	None	None	None	None	None	None
Ductility	Ductile	Ductile	Ductile	Ductile	Ductile	Ductile	Ductile	Brittle
Hardness: As Cast	<400 VHN	130	229	173	223	231	332	406
Hardness: As Brazed		270	240	300	450	310	350	390
Hardness: Heat Treated (2500°F/10 hrs.)		400	320	340	400	310	350	360
Phase Transformations	-	Yes	Suppressed β-α (Ti) <1100°F	Yes	Sluggish Eutectoid	None	None	Eutectoid ~1500°F

Alloys Selected for Service With F-48 To 2500°F:

AS501 (Ti-30V) - Represents minimum liquids in Ti-V system. Ductile alloy, only slight erosion of base metal.

AS514 (V-35Cb) - Higher melting point than AS501. Excellent compatibility with F-48. Cb content should provide good strength properties.



Although the most comprehensive evaluation of each brazing alloy may be best made through the use of the summary data sheets (see Appendix A), some general trends in alloying behavior were evident. For example, the microstructural studies of Ti-Fe and Ti-Cr alloys revealed that rapid grain growth of the Cb-1Zr base alloy had occurred as a result of interdiffusion with the braze alloy. This effect was observed with AS-502 (Ti-5Fe), AS-503 (Ti-10Fe), AS-505 (Ti-10Cr), AS-506 (Ti-20Cr), and AS-526 (Ti-6Fe-4Cr) alloys, all of which flowed above 2700°F. A braze alloy with higher iron content, AS-504 (Ti-20Fe), and the ternary alloy, AS-535 (Ti-13Fe-8Cr) did not exhibit this behavior at 2500°F. Thus, it is evident that accelerated grain growth was caused by high diffusion temperature rather than alloying content per se. It is interesting to note that grain growth occurred in five minutes at the brazing temperature, but did not continue during the 2200°F/65 hour thermal treatment.

Other alloys considered for brazing Cb-1.0Zr or F-48 exhibited no gross interdiffusion reactions during the braze thermal cycles.

2.4.3 Hardness

The hardness traverses served to verify the extent of diffusion and compatibility between braze and base alloys. Brazing alloy AS-506 (Ti-20Cr), which produced both erosion and grain growth in Cb-1.0Zr, exhibited no significant hardness increase in the base metal or braze alloy.

If diffusion of elements in the brazing alloy were the cause of grain growth, one would expect a significant hardness increase in the Cb-1Zr alloy. Since this did not occur, it is possible that grain growth was caused by diffusion of interstitial elements outward from the Cb-1Zr into the brazing alloy. This hypothesis would serve to explain the experimental observations.

Removal of interstitials from the grain boundaries would allow accelerated grain growth by unlocking of dislocation sites. No hardness increase in the Cb-1Zr alloy would occur. The F-48 alloy would not be expected to show grain growth because of its higher interstitial content and, therefore, incomplete removal from grain boundaries.

The effect of the brazing thermal cycle on the hardness of F-48 is illustrated in Fig. 1. Both braze alloys, AS-501 (Ti-30V) and AS-514A (65V-35Cb), form no intermetallic compounds with Cb. However, the higher brazing temperature of AS-514A (3400°F vs. 3000°F for AS-501) resulted in a hardness increase from 250 VHN to 300 VHN of the F-48 base alloy. This result is consistent with the studies by Chang [(10)] on the influence of heat treatment on the properties of refractory metals. The hardness increase observed upon annealing at temperatures above 3250°F has been attributed by Chang to solutioning and reprecipitation of interstitial element compounds during the thermal cycle.

2.4.4 Effect Of Thermal Treatment

The effect of diffusion heat treatment on brazing alloy hardness is summarized in Tables VIII and IX. Brazing alloys for Cb-1.0Zr were exposed for 65 hours at 2200 and 1800°F depending upon the intended service temperature. Brazing alloys for F-48 were exposed at 2500°F for 10 hours. Although each brazing alloy/base metal combination must be considered individually, results indicate that in systems in which solid state transformations are likely to occur, brazing alloy hardness increased as a result of thermal treatment. For example, the Ti-Fe and Ti-Cr systems exhibit eutectoid decomposition into alpha titanium plus Ti-Fe or $TiCr_2$. More specifically, the brazing alloy hardness increased most drastically near the surface of the specimen. This behavior may indicate that the cooling rate from the exposure temperature affects these phase transformations. The surface of the specimen. which cools more rapidly than the center, could then form the transition phase, designated omega,, accounting for the increased hardness. Another factor which would tend to minimize hardness increases near the braze/base metal interface is columbium diffusion which would tend to stabilize the beta phase in titanium or zirconium alloys. As mentioned previously, the hardness of these alloys is increased rapidly if contamination by oxygen or nitrogen occurs. This type of reaction should not be a factor in the observed hardness increases, however, since several brazing alloys containing zirconium or vanadium showed no increase in hardness during thermal treatment.

The effect of the 2500°F/10 hr. thermal treatment on the hardness of F-48 is illustrated by alloy AS-514 (65V-35Cb) (Appendix A). The as-brazed hardness, 300 VHN, has decreased to approximately 240 VHN. This decrease has been attributed to overaging of precipitates (11).

2.4.5 Selection Of Alloys For Additional Evaluation

The criteria for selection of brazing alloys for further evaluation are summarized in Tables VIII and IX. The factors which eliminated certain alloys are underlined. For the Cb-1.0Zr base alloy, alloy AS-537 (Zr-28V-16Ti) was selected for 1800°F service and alloy AS-536 (Ti-6Fe-4Cr) for 2200°F service. The AS-537 alloy was ductile, exhibited excellent compatibility with columbium, and offers the potential for growth to higher melting point alloys. The AS-536 alloy was representative of brazing alloys containing elements which may form intermetallic compounds with columbium. This alloy, however, was ductile and showed negligible change in hardness upon heat treatment. In addition, the alloy would be valuable in determining if any adverse effect existed as a result of grain growth in the Cb-1.0Zr base alloy.

Of the alloys for brazing F-48, only those zirconium-base could be eliminated on the basis of excessive erosion. The other three alloys, AS-501 (Ti-30V), AS-513 (V-20Ti), and AS-514 (V-35Cb) were acceptable, although the brazing temperature of AS-514 was slightly higher than desired. The two alloys finally selected were AS-501 from the Ti-V binary system and AS-514. Both exhibited excellent compatibility with F-48. Alloy AS-514 was chosen mainly because of its columbium content, which was expected to impart high temperature strength.

The important properties of these alloys are tabulated as shown in Table X.

TABLE X

PROPERTIES OF SELECTED BRAZING ALLOYS FOR COLUMBIUM

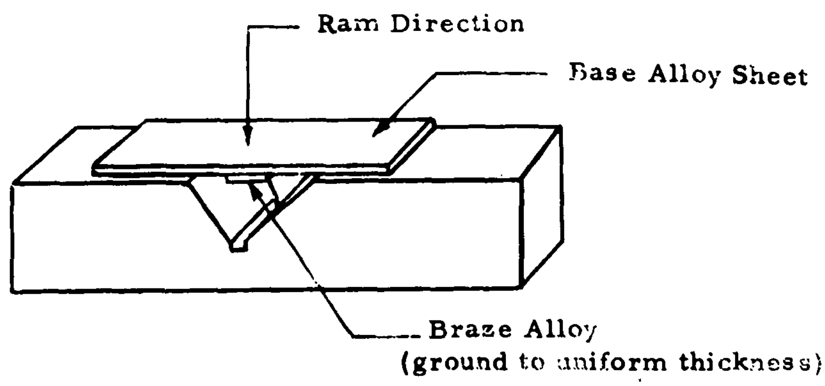
Alloy	Composition Wt. %	Erosion, inches	Brazing Temperature, °F	Hardness As Brazed, VHN
AS-537	Zr-28V-16Ti	None	2250	380
AS-536	Ti-6Fe-4Cr	.002	2850	300
AS-501	Ti-30V	.002	3000	240
AS-514	V-35Cb	.001	3400	350

2.5 EVALUATION OF SELECTED ALLOYS FOR COLUMBIUM

2.5.1 Brazing Thermal Cycle Effects On Parent Metal Transition Temperature

The ductile-to-brittle transition temperature of brazed joints is an important consideration since most component handling and subsequent assembly operations are performed at room temperature. Also, although most refractory metal structures are intended for use at elevated temperatures, the service mission may involve application of stress at much lower temperatures, sometimes sub-zero.

To determine the effects of the brazing thermal cycles on transition temperature, bend specimens were prepared and tested as shown schematically below:



Specimens of each base alloy, Cb-1.0Zr and F-48, were prepared with brazing alloy on the surface, and as non-brazed panels which also received the appropriate brazing thermal cycle. The surface brazing alloy was ground to a uniform thickness of .003 $\pm$ .001 inch.

The brazing alloys investigated were AS-537 (Zr-28V-16Ti) and AS-536 (Ti-6Cr-4Fe) with Cb-1.0Zr, and AS-501 (Ti-30V) and AS-514 (V-35Cb) with F-48 alloy.

It is interesting to note that additional 50 g button heats of each alloy which were melted for this study showed no deviation in melting range from that previously reported. The AS-501 and AS-514 alloys were produced in strip form by forging and rolling 0.5 inch thick buttons to .045" sheet at room temperature. The AS-537 and AS-536 alloys cracked during forging at approximately 50% reduction. These alloys were machined into chips as previously described.

The results of this study are presented in Table XI.

As expected, the Cb-1.0Zr base alloy was ductile at liquid nitrogen temperature (-320°F) for all the conditions tested. The brazing alloys exhibited less ductility. Both AS-537 and AS-536 were cracked after bending at room temperature and -320°F. These cracks did not propagate into the Cb-1.0Zr at either test temperature. Thus, the transition temperature of Cb-1.0Zr is unaffected either by the brazing thermal cycle or by the application of these brazing alloys.

The F-48 alloy was expected to show embrittlement after exposure at 3000°F or above as explained by Chang [10]. The results obtained herein illustrate this behavior. The transition temperature for F-48 alloy exposed to a pseudo-braze cycle at 3400°F for five minutes increased from below room temperature to 300°F. Similarly, the 3000°F thermal exposure increased the bend transition temperature to between 200 and 300°F.

Specimens brazed with AS-514 (V-35Cb) alloy exhibited an additional 200°F increase in transition temperature to 500°F. The hardness of AS-514 was 350 VHN vs. 300 VHN for F-48 in the as-brazed condition. This higher hardness indicates the brazing alloy transition temperature may be above that of F-48 alloy. Bend failure would then occur by crack propagation from the brazing alloy into the F-48 base alloy. The softer, more ductile, AS-501 alloy (Ti-30V) did not increase transition temperature.

TABLE XI

EFFECTS OF THERMAL CYCLES AND BRAZING ALLOYS ON BEND TRANSITION TEMPERATURE OF COLUMBIUM ALLOYS *

Cb-1.0Zr ALLOY

Temperature	Results**	Ultimate Load lbs.	Bend Radius in.	Bend Radius "t"	Specimen *** t	Specimen *** w
PARENT ALLOY						
Heat Treated 2850°F/5 min. /vac.						
Room Temp.	105° Bend @ 103°	110	3/16	4.47	.042	.761
-320°F	105° Bend @ 89.5°	218	1/8	2.98	.042	.762
Heat Treated 2250°F/5 min. /vac.						
Room Temp.	105° Bend @ 100°	98	3/16	4.47	.042	.758
-320°F	105° Bend @ 86°	203	1/8	2.98	.042	.764
BRAZED SPECIMENS						
AS-536 Brazed @ 2850°F/5 min. /vac.						
Room Temp.	105° Bend @ 98°	122	3/16	4.07	.046	.745
-320°F	105° Bend @ 85°	213	1/8	2.72	.046	.689
-320°F	105° Bend @ 85°	246	1/8	2.72	.046	.725
AS-537 Brazed @ 2250°F/5 min. /vac.						
Room Temp.	105° Bend @ 98°	103	3/16	4.07	.046	.629
-320°F	105° Bend @ 87.5°	180	1/8	2.72	.046	.659
-320°F	105° Bend @ 86.3°	197	1/8	2.78	.045	.691

(cont.)

TABLE XI (cont.)

F-48 ALLOY

Temperature	Results**	Ultimate Load lbs.	Bend Radius in.	Bend Radius "t"	Specimen*** t	Specimen*** w
PARENT ALLOY						
Heat Treated @ 3400°F/5 min. /vac.						
Room Temp.	Failure @ 0°	122	1/8	3.68	.034	.717
200°F	Failure @ 37°	187	1/8	3.38	.037	.729
250°F	Failure @ 78°	200	1/8	3.38	.037	.737
300°F	105° Bend @ 91°	117	1/8	3.78	.033	.695
400°F	105° Bend @ 89°	169	1/8	3.57	.035	.708
Heat Treated @ 3000°F/5 min. /vac.						
Room Temp.	Failure @ 17°	172	1/8	3.38	.037	.718
300°F	105° Bend @ 93°	113	1/8	3.78	.033	.695
400°F	105° Bend @ 89°	195	1/8	3.47	.036	.728
F-48 Unheat Treated						
Room Temp.	105° Bend @ 91°	183	1/8	3.57	.035	.725
Heat Treated @ 3400°F/5 min. /vac. + 2500°F/1 hr. /vac.						
Room Temp.	105° Bend @ 91°	144	1/8	3.57	.035	.686

(cont.)

TABLE XI (cont.)

F-48 ALLOY

BRAZED SPECIMENS

Temperature	Results**	Ultimate Load lbs.	Bend Radius in.	Bend Radius "t"	Specimen *** t	Specimen *** w
AS-514A Brazed @ 3400°F/5 min. /vac.						
300°F	Failure @ 31°	138	1/8	3.21	.039	.584
400°F	Failure @ 37°	135	1/8	3.29	.038	.592
450°F	Failure @ 62°	87.5	1/8	3.13	.040	.319
500°F	105° Bend @ 92°	87	1/8	3.38	.037	.404
500°F	105° Bend @ 93°	177	3/16	4.45	.042	.613
AS-501A Brazed @ 3000°F/5 min. /vac.						
150°F	Failure @ 22°	173	1/8	2.98	.042	.669
160°F	105° Bend @ 92°	124	1/8	3.47	.036	.588
200°F	Failure @ 64°	151	1/8	3.29	.038	.669
200°F	105° Bend @ 91°	112	1/8	3.57	.035	.665
300°F	105° Bend @ 93°	96	1/8	4.04	.031	.677

* Head rate: 0.05 in. /min.

** Bend angle after springback from 105°.

*** t = Specimen thickness - inches
w = Specimen width - inches

It is interesting to note that F-48 room temperature bend ductility may be restored by exposure at 2500 to 2750°F following the 3400°F/5 min. pseudo-braze cycle (Table XII). If such a thermal arrest were incorporated into the brazing cycle, joint ductility would be enhanced.

2.5.2 Brazed Joint Strength

The tensile-shear strengths of brazed, simple lap joints are summarized in Table XIII. The joints made of each brazing alloy were tested at the intended service temperature, 1800 and 2200°F with Cb-1.0Zr and 2500°F with F-48 alloy. In addition, the Cb-1.0Zr alloy specimens were tested at room temperature, and the F-48 alloy specimens were tested above the transition temperature, i.e., 500°F. At room temperature or 500°F, joint failure occurred in the parent alloy. At the service temperatures, failure occurred in the brazing alloys with the exception of specimens brazed with AS-514 alloy. This alloy exhibited excellent strength at 2500°F with failures occurring in the parent alloy.

In addition to testing conditions and materials, the apparent shear strength of simple brazed lap joints is also affected by joint clearance, joint overlap, parent metal thickness, and fillet size. It should therefore be emphasized that strength values reported herein are valid only for the particular joint geometry given in Table XIII. For the given conditions, the braze shear strengths were gratifying, indicating useful strength for all the brazing alloys at their respective service temperatures.

2.5.3 Coating Compatibility Studies

Six simple lap joint specimens of each brazing alloy were prepared for evaluation with representative protective coatings for columbium-base alloys. Two specimens of each brazing alloy were supplied to three companies engaged in development of protective coating for columbium (Chance Vought, Thompson-Ramo-Woolridge, and General Electric). At this writing, results have been obtained only with the General Electric LB-2 coating system.

The LB-2 coating is applied as a cold slurry by dipping, painting, or spraying. The base-coat slurry consists of Al-10Cr-2Si alloy suspended in an acetone-xylene vehicle. The top coat slurry consists of an aluminum paste suspended in an acetone-xylene vehicle. After air drying for several hours, the slurry coated specimen is diffusion heat-treated in purified argon for one hour at 1900°F. During heat-up, the temperature is maintained at 500°F for 30 minutes to allow evolution of organic material from the slurries.

TABLE XII

SUMMARY OF BEND TRANSITION TEMPERATURES OF COLUMBIUM ALLOYS EXPOSED TO BRAZING THERMAL CYCLES

Base Alloy	Brazing Alloy	Thermal Exposure	Transition Temperature	Remarks
Cb-1Zr	None	2850°F/5 min.	$<$-320°F	
Cb-1Zr	AS-536	2850°F/5 min.	$<$-320°F	Braze failed at room temperature. No crack propagation.
Cb-1Zr	None	2250°F/5 min.	$<$-320°F	
Cb-1Zr	AS-537	2250°F/5 min.	$<$-320°F	Braze failed at room temperature. No crack propagation.
F-48	None	3400°F/5 min.	300°F	
F-48	None	3400°F/5 min. + 2500°F/1 hr.	$<$R.T.	
F-48	AS-514	3400°F/5 min.	500°F	
F-48	None	3000°F/5 min.	$<$300°F	
F-48	AS-501	3000°F/5 min.	200°F	

TABLE XIII

TENSILE SHEAR PROPERTIES - BRAZED LAP JOINTS (1)

Base Alloy	Braze Alloy	Overlap in.	Overlap "t"	Test Temp. °F	Braze Shear (2) Strength, ksi	Parent Alloy (2) Tensile Strength, ksi	Location Of Failure
Cb-1Zr	AS-536	.099	2.3	R. T.	16.8	39.4	P. M.
"	"	.073	1.7	R. T.	25.4	42.0	P. M.
"	"	.095	2.2	2200	4.5	9.7	Braze
"	"	.090	2.1	2200	5.6	11.7	Braze
"	"	.120	2.9	2200	3.1	8.95	Braze
Cb-1Zr	AS-537	.099	2.3	R. T.	15.8	37.0	P. M.
"	"	.099	2.3	R. T.	16.1	37.6	P. M.
"	"	.090	2.1	1800	5.9	12.3	Braze
"	"	.090	2.1	1800	12.7	26.6	Braze
"	"	.095	2.2	1800	8.8	19.3	Braze
F-48	AS-501	.054	2.5	500	29.8	73.5	P. M.
"	"	.048	2.4	500	27.6	66.2	P. M.
"	"	.046	2.4	2500	5.8	13.7	Braze
"	"	.053	2.8	2500	4.8	13.5	Braze
F-48	AS-514	.053	2.8	500	26.9	75.0	P. M.
"	"	.055	2.6	500	16.0	42.3	P. M.(3)
"	"	.061	2.9	2500	7.7	22.1	P. M.
"	"	.053	2.65	2500	9.2	24.4	P. M.

(1) Test conditions - elevated temperature tests conducted in vacuum - 4-6 $\times 10^{-4}$ mm Hg (Head Rate: .01 in./min.) Joint clearance - zero nominal.

(2) Values underlined represent the indicated shear or tensile strength when failure did not occur in this area of the joint.

(3) Brittle parent metal failure.

The first specimens prepared demonstrated poor compatibility between LB-2 coating and the brazing alloys. After diffusion heat treatment at 1900°F, the coating penetrated the braze base alloy interface, reacted with the alloy, and produced a separation or lifting of the brazing alloy fillet. This interaction was believed to be promoted by the atomic mismatch existing at the braze/base metal interface which served as a diffusion path for aluminum from the slurry. To verify this, each brazing alloy was LB-2 coated individually, in the as-cast condition. In this case, no excessive diffusion reactions occurred and the specimens appeared uniformly coated.

A second series of brazed lap joints were coated using only the basecoat slurry of Al-10Cr-2Si alloy. In this case, the excess aluminum was not present to sustain the diffusion reaction, and specimens had an excellent appearance, but have not yet been oxidation tested.

Further studies of the LB-2 coating process, as well as evaluation of other protective coatings, will be continued.

2.5.4 Sample Components With Brazed Joints

To demonstrate the application of these brazing alloys to practical structures, several components were brazed as shown in Fig. 2. In each instance, the brazing alloy demonstrated good wettability and flow, producing sound, well filleted joints.

Part one demonstrates a typical tube-to-fin joint brazed with AS-537 alloy at 2250°F. The second part represents a corrugated structure such such as those utilized in skin panels. The base alloy in this case was FS82 (Cb-33Ta-.75Zr) brazed with AS-537. Exceptional flow was evident through .5 inch wide lap joints.

The third part demonstrated the applicability of brazing to a leading-edge type structure. The part shown was fabricated from unalloyed tungsten, and brazed with AS-521 (Cb-20V) alloy at 4250°F. This type component was also brazed successfully utilizing F-48 alloy with AS-501 alloy at 3000°F.

3. BRAZING ALLOYS FOR TUNGSTEN

3.1 BACKGROUND

All available binary phase relationships for tungsten are presented in Table XIV (3). No intermetallic phase or eutectic formation are found in tungsten binary alloys containing molybdenum, tantalum, columbium, titanium, platinum, palladium, chromium, and probably vanadium. The tungsten-chromium system, however, exhibits solid state immiscibility from 10-98% tungsten.

3.2 BRAZING ALLOY DESIGN

Goal - To develop a brazing alloy for service to 3500°F on unalloyed tungsten sheet.

3.2.1 Requirements

Brazing alloy should be compatible with W, i.e., no brittle intermetallic compound formation - no low melting ($<$ 3700°F) phases formed during brazing or subsequent service.

Solidus temperature of the brazing alloy should be in range 3700 to 4300°F for 3500°F service. The liquidus temperature should be no more than 200°F above the solidus to avoid liquation during the brazing cycle (3900 to 4500°F).

Brazed joints should possess useful ductility from the brittle-to-ductile transition temperature for tungsten to the service temperature.

Brazing alloy coefficient of thermal expansion should be similar to the base metal.

Brazing alloy should have useful strength at 3500°F.

3.2.2 Considerations

Of the elements known to be compatible with tungsten, only Cb, Mo, and Ta have melting points above the 3500°F temperature goal and thus show promise as major constituents of the brazing alloys. The remaining elements compatible with tungsten should be useful as temperature depressants, to obtain the desired brazing temperature in binary alloy systems.

TABLE XIV - SURVEY OF TUNGSTEN BINARY ALLOY SYSTEMS*

System	Wt.% Soluble X in W	Wt.% Soluble W in X	Low Melting Phases °F	Known Sigma Phase	Known Intermetallics
W-Al	2.4 (2372°F)	1.5 (1202°F)	None	None	$W\text{-}Al_{12}$ $W\text{-}Al_5$ $W\text{-}Al_4$
W-B	Very low	?	Yes(above 3632°F)	None	$W\text{-}B$(5.56B) W_2B(2.86B) W_2B_5(12.82B)
W-Be	?	?	Yes	None	Be_2W(91.08W) Probably $Be_{13}W$(61.07W)
W-C	0.05	0	Eut. $W\text{-}W_2C$ (1.5C)4487°F Eut. $W_2C\text{-}WC$(4.5C)4577°F	None	W_2C(3.16C) W-C (6.13C)
W-Cb	100	100	No	None	None
W-Co	0.3	40 - 2696°F 32 - 2012°F 4.5- 1292°F	Eut. 45W-2696°F	?	$W\text{-}Co_3$(50.98W) $W_6\text{-}Co_7$(72.77W)
W-Cr	100 2724°F Solid state immiscibility (10-98%W)	100 2724°F	None	None	None
W-Cu	Insoluble	Insoluble	-	-	-
W-Fe	0.8@ 2984°F Little change with temperature	33 @ 2804°F 4.5 @ 1292°F	Min. 15W-2777°F	None	$W\text{-}Fe_2$(62.22W) W_2Fe_3(68.70W) W_6Fe_7(73.84W)
W-Ge	?	?	?	?	No compounds found (sintered samples)
W-Hf	?	?	?	?	$Hf\text{-}W_2$
W-Mn	W insoluble in liquid Mn		?	?	?
W-Mo	100	100	None	None	None

(continued)

TABLE XIV (Continued)

System	Wt.% Soluble X in W	Wt.% Soluble W in X	Low Melting Phases °F	Known Sigma Phase	Known Intermetallics
W-Ni	.3@2732°F	40(2732°F) 32(1472°F)	Eut. 2732°F(45W)	None	W-Ni_4(43.93W)
W-Os	5.1	47.2	?	?	Prob.-W_3Os(74.37W)
W-Pd	Negligible	30(max)	Solidus of 21% W Alloy 2552°F	None	None
W-Pt	4 to 6	62(max)	None	None	None
W-Re	?	?	?	Yes	Yes
W-Rh	0.8(max)	20(max)	?	None	H.C.P. phase 30 to 60% W
W-Si	0.9@3272°F	0	Eut. 4010°F(4Si) 3650°F(18Si) 2534°F(95Si)	None	W_3-Si_2 W-Si_2
W-Ta	100	100	No	None	None
W-Ti	8@3416°F 4@1319°F	50(3416°F-Beta Ti 28(1319°F-Beta Ti .08-Alpha Ti	No	None	None
W-V	?	Prob. 40%	?	?	?
W-Zr	3@3900°F	8@3020°F Beta Zr 0.5-Alpha Zr	Eut. 3020°F(18W)	None	Zr-W_2

* All data from: Hansen, M. "Constitution of Binary Alloys, 2nd Ed.", McGraw-Hill, 1958.

The ductility of the Cb and Ta base brazing alloys should be adequate since both elements have ductile-to-brittle transition temperatures lower than tungsten. Molybdenum generally has a transition temperature above room temperature, but not above that of tungsten. However, from the standpoint of braze ductility, columbium and tantalum alloys appear more promising than molybdenum alloys.

A comparison of thermal expansion coefficients of W, Mo, Ta, and Cb (Table XV) shows that Ta most closely matches W. The expansion coefficients of Cb and Mo are less favorable.

3.2.3 Alloy Selection

Based on the above considerations, several binary alloy systems were selected for W brazing studies. For comparison with compatible alloys, one alloy system, Cb-Ni, was selected in which Ni will form intermetallic phases with Cb and W. The Ta-Pd alloy system was selected to determine the effectiveness of Pd as a temperature depressant. (Table XVI).

3.3 EXPERIMENTAL PROCEDURE

3.3.1 Preparation Of Alloys

Alloy preparation generally followed the same procedure as previously discussed in the section "Brazing Alloys For Columbium". The tantalum base alloys with Ti, V, and Pd, however, proved difficult to arc-melt due to excessive volatilization of the alloying element. To avoid this condition, these alloys were first melted as master button heats (50% alloying element) and chemically analyzed. These master alloys were then used as alloying additions during subsequent melting to the desired brazing alloy composition.

3.3.2 Preparation Of Brazed Specimens

For the tungsten brazing studies, high purity, powder metallurgy sheet was used. This material was from the same lot (PM-B) used for the tungsten welding studies (11). Small panels 1" X 1" were electrolytically polished .005" per side to remove surface contamination. Interstitial element content was reduced to: carbon - 10 $\pm$ 4 ppm, oxygen - 9 $\pm$ 2 ppm, nitrogen - 1.5 $\pm$ 1 ppm, and hydrogen - 0.3 ppm utilizing this procedure.

A fixed volume of brazing alloy, .075 cc, was applied to each panel and the melting range was evaluated as previously described.

TABLE XV

MEAN LINEAR COEFFICIENTS OF THERMAL EXPANSION

FOR REFRACTORY METALS

Temperature, ^{o}F	Coefficient Of Expansion From $85^{o}F$ To Temperature in./in./$^{o}F \times 10^{-6}$			
	W	Mo	Ta	Cb
600	-	2.89	-	4.08
1200	-	2.98	-	4.27
2000	-	3.32	-	4.63
2500	-	3.53	-	4.76
3000	-	3.98	3.74	4.84
3400	-	4.52	3.92	4.94
3800	-	5.17	4.20	5.04
4000	4.19	-	-	5.08
4200	-	5.49	4.56	-
4400	4.31	-	-	-
4600	-	6.04	5.15	-
4700	-	6.25	-	-
4800	4.47	-	-	-
5000	-	-	5.86	-
5200	4.65	-	6.21	-
5600	4.93	-	-	-
6000	5.34	-	-	-
6100	5.45	-	-	-

TABLE XVI

BRAZING ALLOYS FOR SERVICE WITH UNALLOYED TUNGSTEN

Alloy Designation	Nominal Composition Wt. %	Expected Melting Range, °F Solidus	Liquidus
AS-526	Ta - 15 Ti	4180	4320
AS-527	Ta - 25 Ti	3920	4060
AS-528	Ta - 15 V	4170	?
AS-529	Ta - 25 V	3810	?
AS-530	Ta - 15 Pd	?	?
AS-531	Ta - 25 Pd	?	?
AS-515	Cb -	4470	4470
AS-518	Cb - 10 Ti	4020	4340 (?)
AS-519	Cb - 20 Ti	3790	4260 (?)
AS-520	Cb - 10 V	4060	4160
AS-521	Cb - 20 V	3760	3880
AS-523	Cb - 5 Ni	?	?
AS-522	Cb - 15 Ni	4000	?
AS-533	Mo - 20 Ti	4160	4320
AS-534	Mo - 30 Ti	3920	4120

3.4 RESULTS AND DISCUSSION

3.4.1 Melting Range Determinations

Complete data for these alloys are reported in summary data sheets (see Appendix B). The melting range determinations are summarized in Table XVII. Two alloys, AS-534 (Mo-30Ti) and AS-527 (Ta-25Ti) could not be melted at 4400°F and were dropped from consideration. Alloys from the Cb-B and Cb-V systems also exhibited melting ranges higher than expected. As previously mentioned, the Cb-B alloys were evaluated for tungsten brazing when their melting range proved too high for use in brazing columbium. The Ta-Pd, Ta-V, and Ta-Ti alloys were prepared first as 50-50 w/o master alloys. The melting ranges of these alloys are included for general interest.

3.4.2 Wettability And Flow

The brazing alloy wettabilities were excellent, except for the alloys AS-522 (Cb-15Ni), AS-529 (Ta-25V), and AS-531 (Ta-25Pd). While these alloys flowed on the tungsten, the flow line stopped abruptly with the brazing alloy surface presenting a wavy appearance (Fig. 3). Apparently, alloy solidification occurred prematurely, by loss of the temperature depressant, either by volatilization or by diffusion into the base metal.

3.4.3 Metallographic Studies

Metallographic examination revealed no gross erosion of the tungsten by any of the brazing alloys. The maximum solutioning - .003" - occurred with the AS-539 alloy (Cb-3B).

Both metallographic examination and hardness traverses were used to study the effects of the brazing cycle and diffusion heat treatment at 3500°F/2 hrs. The hardness traverses were particularly informative, revealing that in several brazing alloy systems, the as-brazed hardness had decreased by a factor of two from as-cast values (Table XVIII).

The microstructural studies of AS-517 (Cb-2.2B) indicated a hypoeutectic alloy consisting of columbium solid solution and eutectic (Appendix B). The apparent decrease in hardness after brazing at 4000°F resulted from liquation (separation of the eutectic) during brazing. The center portion of the brazed panel had a preponderance of columbium solid solution after run-out of the eutectic. A hardness traverse along the brazing

TABLE XVII

SUMMARY OF MELTING RANGE DETERMINATIONS - BRAZING ALLOYS FOR TUNGSTEN

Alloy	Nominal Composition Wt. %	Melting Range, °F Expected	Melting Range, °F Actual	As-Cast Hardness VHN	Ductility
AS-516	Cb - 1.0 B	- -	> 3800 sol. > 4000 liq.	232	Ductile
AS-517 *	Cb - 2.2 B	2930 2930	> 3800 < 4000	301	Ductile
AS-539 *	Cb - 3.0 B	- -	> 3800 < 4000	323	Slightly Ductile
AS-518	Cb - 10 Ti	4020 4340	> 4300 4400	163	Ductile
AS-519	Cb - 20 Ti	3790 4260	4000 4100	192	Ductile
AS-520 *	Cb - 10 V	4060 4160	4100 4400	263	Ductile
AS-521 *	Cb - 20 V	3760 3880	4000 4250	318	Ductile
AS-522	Cb - 15 Ni	4000 -	- < 4000	597	Brittle
AS-523	Cb - 5 Ni	- -	4100 4400	247	Slightly Ductile

(cont.)

TABLE XVII (cont.)

Alloy	Nominal Composition Wt. %	Melting Range, °F Expected	Actual	As-Cast Hardness VHN	Ductility
AS-529	Ta - 25 V	3810 -	<3950 sol. 4250 liq.	393	Ductile
AS-530	Ta - 15 Pd	-	>4275 liq.	329	Ductile
AS-531	Ta - 25 Pd	- -	~3600 liq.	879	Brittle
AS-534 *	Mo - 30 Ti	3920 4120	>4400 liq.	462	Brittle
AS-527 *	Ta - 25 Ti	3920 4060	> 4400 sol.	-	Ductile

* Alloys with melting range higher than expected.

Master Alloys	-	Ta - 50 Pd	-	3300
		Ta - 50 V	-	3300-3500
		Ta - 50 Ti	-	3300-3700

TABLE XVIII

BRAZE ALLOY SELECTION CRITERIA - UNALLOYED TUNGSTEN BASE METAL FOR SERVICE TO 3500°F

Criteria	Property Requirement	AS517 Cb-2.2B	AS539 Cb-3.0B	AS518 Cb-10Ti	AS519 Cb-20Ti	AS520 Cb-10V	AS521 Cb-20V	AS522 CB-15Ni	AS523 Cb-5Ni	AS529 Ta-25V	AS531 Ta-25Pd
Melting Range											
Solidus	3700-4300	>3800	>3800	>4300	4000	4100	4000	--	4100	<3950	--
Liquidus (within 200°F of solidus)	3900-4500	<4000	< 4000	4400	4100	4400	4250	<4000	4400	4250	<3600
Wettability	Contact Angle	3°	6°	12°	15°	1[illegible]°	15°	Poor flow	16°	51°	Poor flow
Compatibility Base Metal/ Erosion	<.002"	None	.003"	None	None	None	None	None	None	None	Not investigated.
Diffusion Reactions	W Hardness Increase (3500°F/2 hrs. exposure)	Yes	Yes	Yes	No	Yes- near inter- face	Yes	Yes at inter- face	Yes near inter- face	Yes	
Ductility:	Ductile	Ductile	Slightly Ductile	Ductile	Ductile	Ductile	Ductile	Brittle	Slightly Ductile	Ductile	Brittle
Hardness:											
As Cast	<400 VHN	301	323	163	192	263	318	492	247	393	879
As Brazed	<400 VHN	155	680-524	150	193	200-144	230	285	146	380	---
Exposed @ 3500°F/ 2 hours	<400 VHN	152	400-580	150	280	180	260	300	150	460	---
Phase Transformations		None	None	None	None	None	None	None	None	None	None

alloy (Fig. 4) illustrates the true hardness of the eutectic. The AS-539 alloy (Cb-3B) may be slightly hyper-eutectic as indicated by high hardness, 600 VHN, resulting from intermediate phase formation, i.e., Cb_3B_2 or CbB. Similar reasoning would also apply to alloys from the Cb-Ni binary system, AS-522 (Cb-15Ni) and AS-523 (Cb-5Ni).

3.4.4 Hardness

The Cb-V binary alloys, AS-520 (Cb-10V) and AS-521 (Cb-20V) also showed hardness decreases after brazing. From the wavy appearance of the alloy surface, it appeared that volatilization of vanadium may account for this hardness decrease. At 4400°F, the vapor pressure of vanadium is approximately 4 mm Hg, indicating rapid evolution in the 10^{-4} mm Hg vacuum.

The thermal exposure at 3500°F/2 hrs. increased the hardness of AS-519 (Cb-20Ti) from 193 to 280 VHN. Similarly, AS-529 (Ta-25V) increased from 380 to 460 VHN. In both cases, a pronounced dendritic pattern present in the as-brazed condition was removed by the thermal treatment.

The hardness of the tungsten base metal after all brazing cycles (4000 to 4400°F) was uniformly 340 to 360 VHN. Only the panel brazed with alloy AS-539 (Cb-3B) indicated a hardness increase near the braze/base metal interface. After exposure to 3500°F/2 hrs., the tungsten panels brazed with both Cb-B alloys increased in hardness uniformly to 400 VHN, presumably as a result of boron diffusion from the brazing alloys.

Tungsten panels brazed with Cb-V binary alloys also increased hardness to 400 VHN, particularly near the braze/base metal interface. This increased hardness was also evident for the panel brazed with AS-529 (Ta-25V) alloy. In each case, the depth of hardening increased with increasing vanadium content.

The Cb-Ni binary alloys produced hardness peaks in the tungsten at the braze interface after thermal exposure. This peak hardness was more pronounced with AS-522 (Cb-15Ni) alloy and may indicate the formation of an intermetallic phase at the interface.

3.4.5 Selection Of Alloys For Additional Evaluation

The criteria for selection of brazing alloys for further evaluation are summarized in Table XVIII. The factor which eliminated certain alloys were underlined. Alloys from four brazing alloy systems, Cb-2.2B, Cb-10 or 20Ti, Cb-10 or 20V, and Cb-5Ni have shown properties which merit further evaluation. Two of these alloys, AS-517 (Cb-2.2B) and AS-519 (Cb-20Ti) have been tentatively selected for additional evaluation. Their selection would allow evaluation of alloys exhibiting two distinctly different interactions with unalloyed tungsten. The AS-517 alloy increased the tungsten hardness after thermal exposure at 3500°F/2 hrs., while AS-519 had no effect. Conversely, the hardness of AS-519 itself increased after thermal exposure, while the AS-517 alloy hardness remained equivalent to the as-brazed value. Both alloys exhibited excellent wettability and flow, possessed adequate ductility, and have a melting range commensurate with the 3500°F service temperature.

4. CONCLUSIONS

The following conclusions can be made, based on the results of this study to date:

1. Brazing alloys have been identified with melting ranges and compatibility with base metals under the following conditions:

Base Alloy	Braze Alloy	Brazing Temp.	Service Temp.
Cb-1.0Zr	AS-537 (Zr-28V-16Ti)	2250°F	1800°F
Cb-1.0Zr	AS-536 (Ti-6Fe-4Cr)	2850°F	2200°F
F-48	AS-501 (Ti-30V)	3000°F	2500°F
F-48	AS-514 (V-35Cb)	3400°F	2500°F
Unalloyed W	AS-517 (Cb-2.2B)	4000°F	3500°F
Unalloyed W	AS-519 (Cb-20Ti)	4100°F	3500°F

2. The alloys for brazing columbium have demonstrated excellent wettability and diffusion compatibility, combined with adequate strength at indicated service temperatures.

3. Based on reported data, several brazing alloys (such as AS-513 (V-20Ti)) not selected for additional property evaluation may be applicable for columbium and tungsten brazing.

4. The brazing alloys evaluated in terms of a specific columbium base alloy should also be applicable to other columbium alloy systems.

REFERENCES

1. Betterton, J. O., Jr., and Easton, D. S., "Silver-Zirconium System", Trans. AIME 212 (1958), p. 470.

2. Nowikow, Alexej and Baer, Hans Gunter, "Ternary System Titanium-Vanadium-Zirconium", Zeitschrift for Metallkunde 49 (1958), p. 195.

3. Hansen, M., Constitution Of Binary Alloys, 2nd Edition, McGraw-Hill, New York, 1958.

4. Dwight, A. E., "Alloying Behavior Of Columbium", Columbium Metallurgical Symposium of AIME, Lake George, New York, 1960.

5. Miller, G. L., "Metallurgy Of The Rarer Metals No. 6, Tantalum And Niobium", Academic Press, Inc., New York, 1959.

6. Elyutrn, V. P. and Funko, V. F., "Some Data On The Phase Diagram Of The Chromium-Columbium System", Brutcher Translation 4304, 1958.

7. Personal Communication from G. M. Slaughter, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

8. Wulff, J. and Brophy, J., "Refractory Metal Phase Diagrams", Quarterly Progress Report on Contract AF-33(616)-7157, ASD, Nuclear Metals Inc., January 31, 1961.

9. Emelyanov, V. S., Godin, Ya. G., and Evstyuklin, A. I., "Investigation Of The System Zirconium-Tantalum", Atomnaya Energiya 2 (1957), p. 42.

10. Chang, W. H., "A Study Of The Influence Of Heat Treatment On Microstructure And Properties Of Refractory Alloys", General Electric. Preliminary data on Contract AF-33(616)-7125.

11. Clark, J. W., "Physical Metallurgy Of Welding Tungsten And Tungsten-Base Alloys", General Electric, ASD TR 61-584 on Contract AF-33(616)-7484.

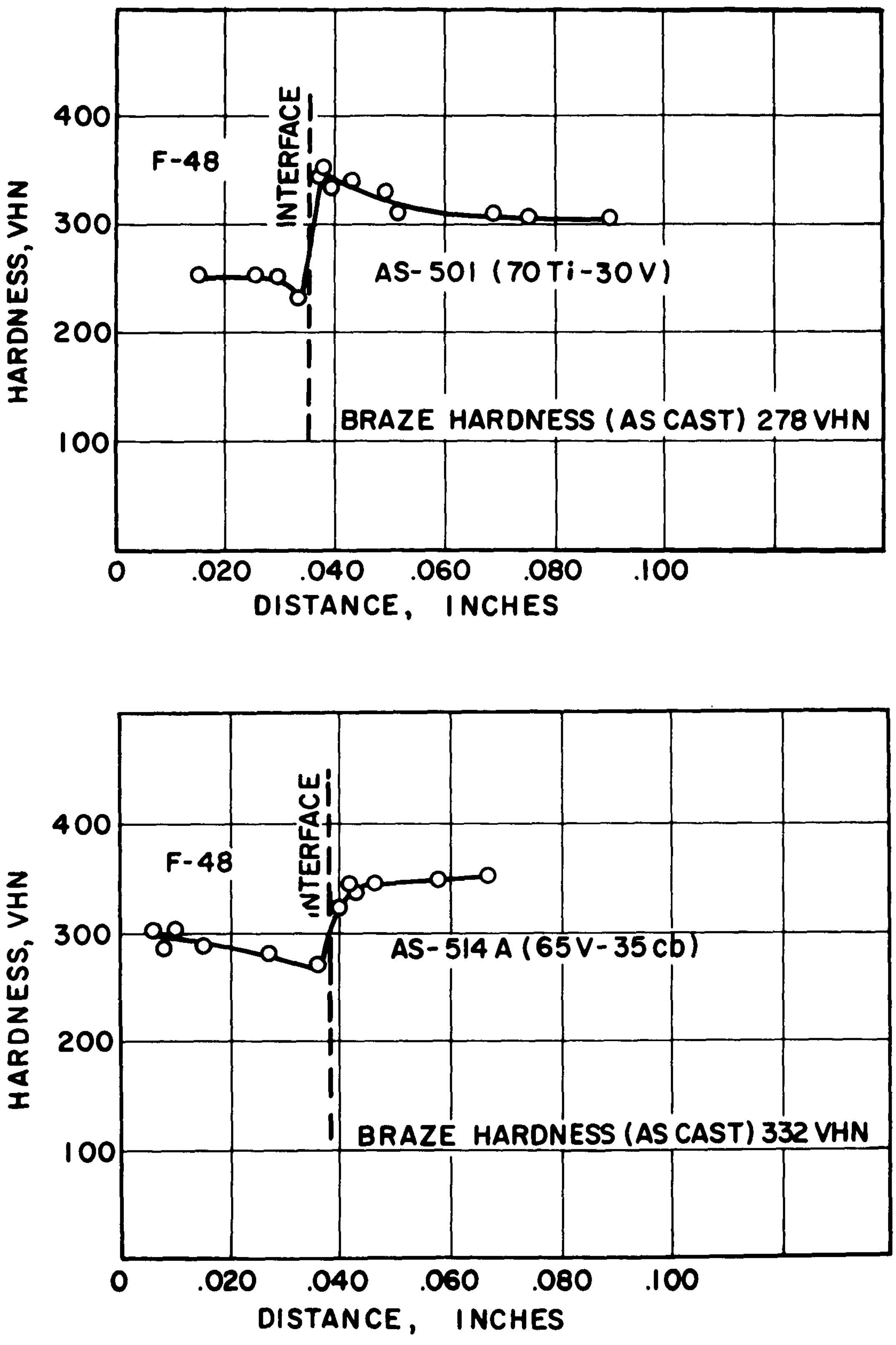


Figure 1 - Hardness Traverse - F-48 Alloy Panels After Brazing

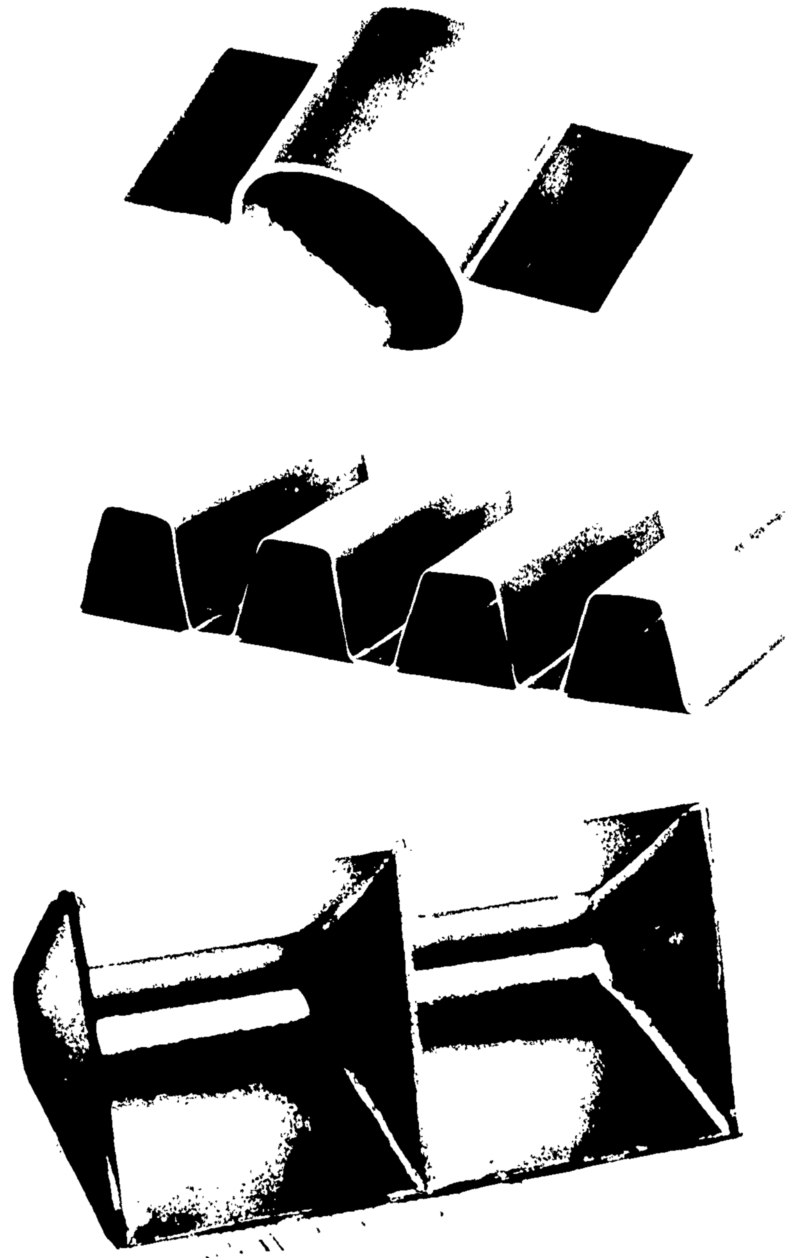
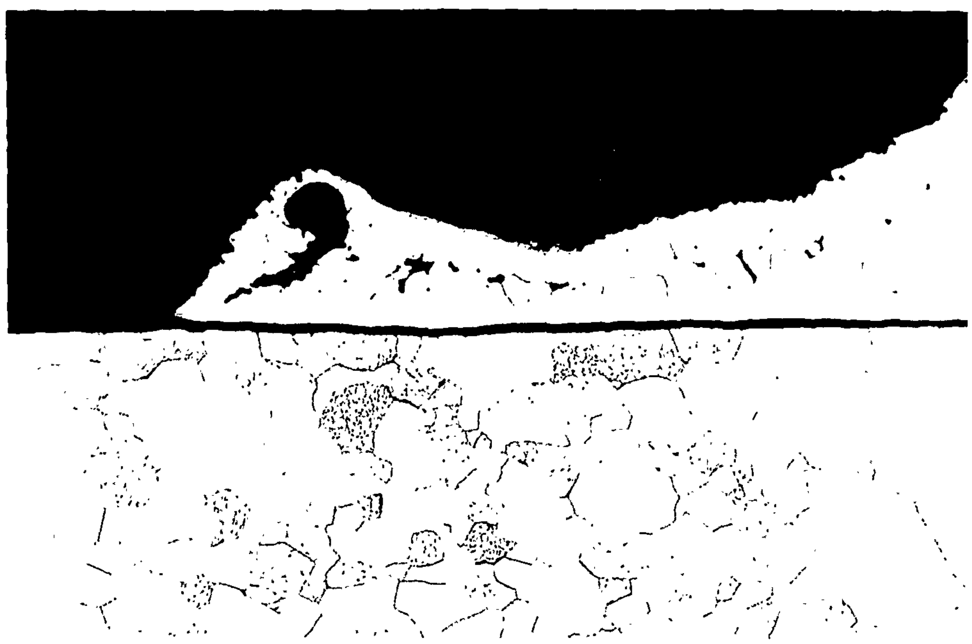


Figure 2 - Representative Brazed Joints In Fabricated Refractory Metals

Top - Cb-1Zr Alloy Brazed With AS-537 (Zr-28V-16Ti) at 2250°F

Middle - Fansteel 82 Alloy - Braze Alloy AS-537 at 2250°F

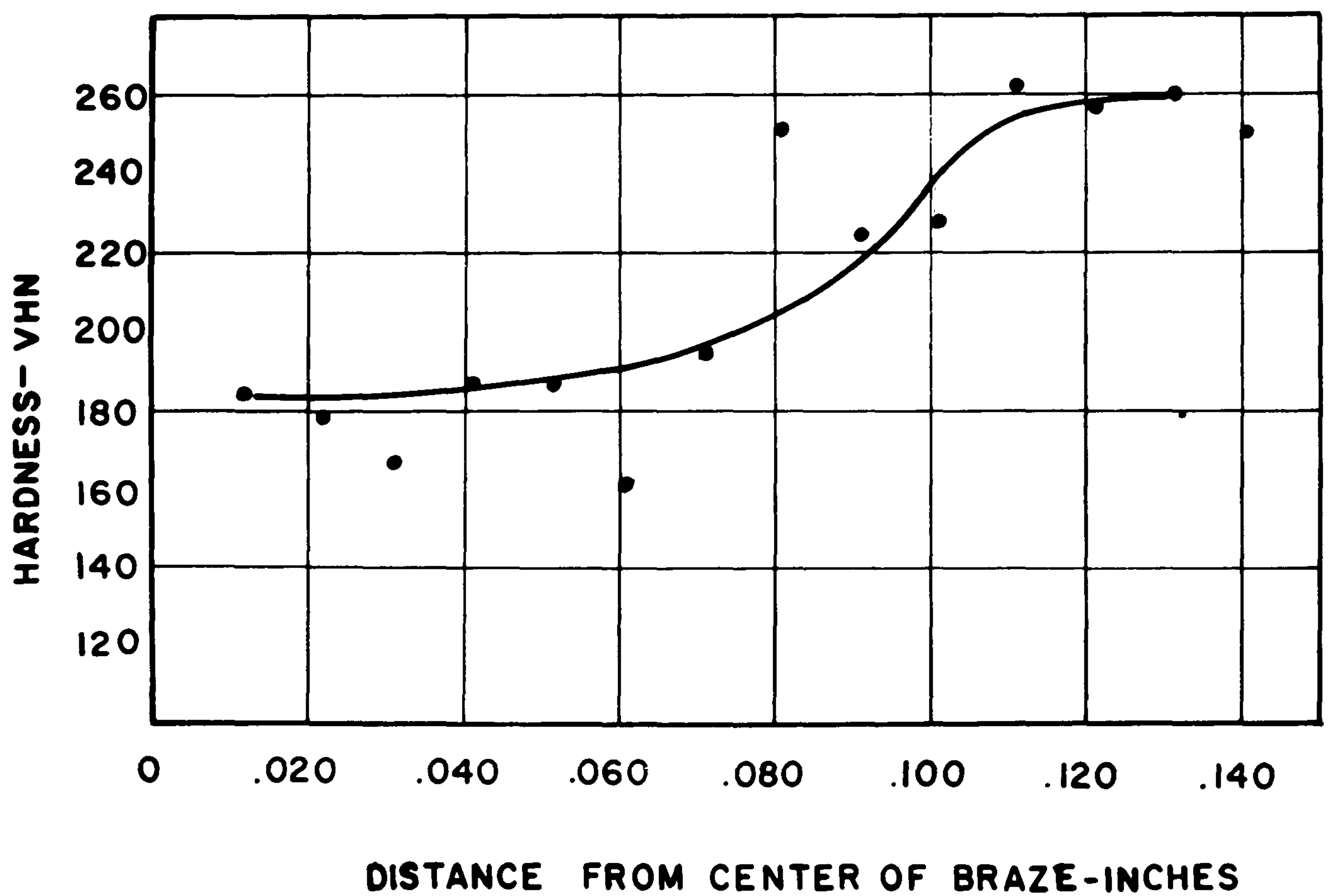
Bottom - Unalloyed Tungsten - Braze Alloy AS-521 (Cb-20V) at 4250°F



4936-3152 100 ×

Figure 3 - Microstructure Of AS-529 (Ta-25V) Alloy On Unalloyed Tungsten. Brazed At 4250°F/5 minutes.

Figure 4 - HARDNESS TRAVERSE FOR AS-517(Cb-2.2B) ALLOY



APPENDIX A

BRAZING ALLOYS FOR COLUMBIUM

SUMMARY DATA SHEETS

BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Cb-1.0Zr

Braze Alloy Designation	Nominal Composition	Melting Range °F Expected	Melting Range °F Actual	Hardness As Cast VHN	Ductility As Cast
AS502	Ti-5Fe	2680 2780	> 2725 < 2850	506	Ductile

Wettability -

Time:	5 min.	5 min.	5 min.
Temperature:	2725°F	2850°F	2980°J
Contact Angle:	None	-	22°
Mag:	1.5	1.5	1.5

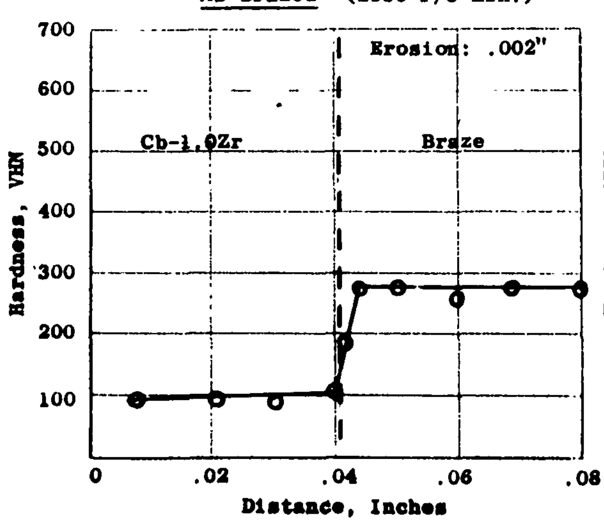
Microstructure -
As Brazed (2980°F/5 min.)

4977-1949 100X

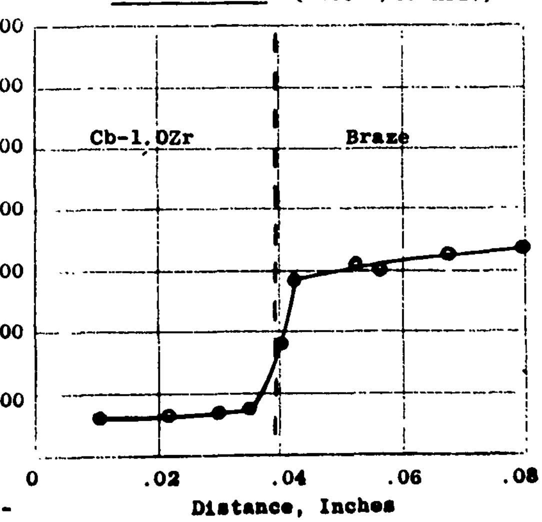
Heat Treated (2200°F/65 hr.)

5408-2111 100X

Hardness Traverse -
As Brazed (2980°F/5 min.)



Heat Treated (2200°F/65 hrs.)



BRAZE ALLOY

SUMMARY DATA SHEET

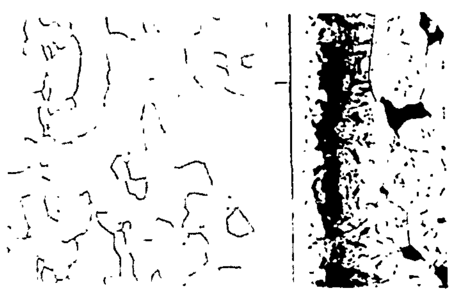
Base Metal: Cb-1.0Zr

Braze Alloy Designation	Nominal Composition	Melting Range °F Expected	Melting Range °F Actual	Hardness As Cast VHN	Ductility As Cast
AS503	Ti-10Fe	2390 2600	< 2725	348	Ductile

Wettability -

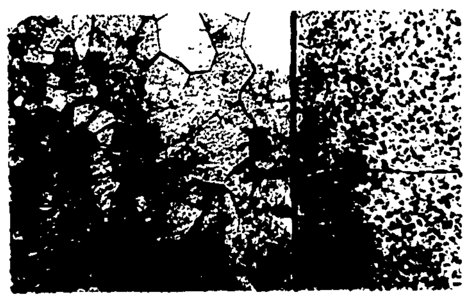
Time: 5 min.
Temperature : 2725°F
Contact Angle : 17°
Mag: 1.5

Microstructure -
As Brazed (2725°F/5 min.)



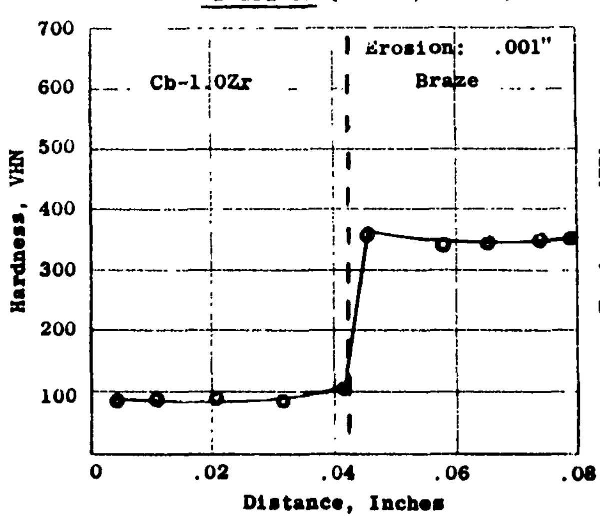
4983-1956 100X

Heat Treated (2200°F/65 hr.)

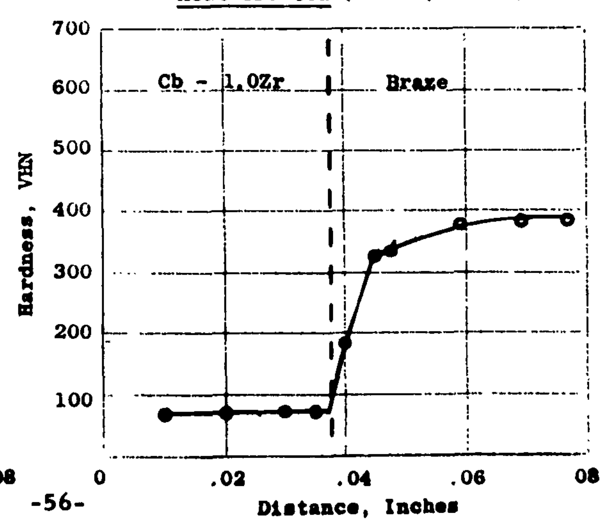


5409 - 2109 100X

Hardness Traverse -
As Brazed (2725°F/5 min.)



Heat Treated (2200°F/65 hr.)



BRAZE ALLOY

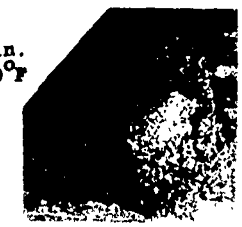
SUMMARY DATA SHEET

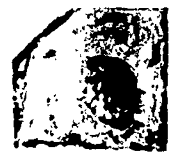
Base Metal: Cb-1.0Zr

Braze Alloy Designation	Nominal Composition	Melting Range °F Expected	Melting Range °F Actual	Hardness As Cast VHN	Ductility As Cast
AS504	Ti-20Fe	2060 2280	< 2100 2200	499	Brittle

Wettability -

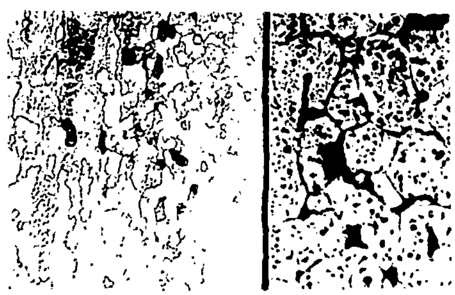
Time:	5 min.	5 min.	5 min.
Temperature :	2100°F	2200°F	2500°F
Contact Angle :	--	5°	3°
Mag:	1.8	1.8	1.1



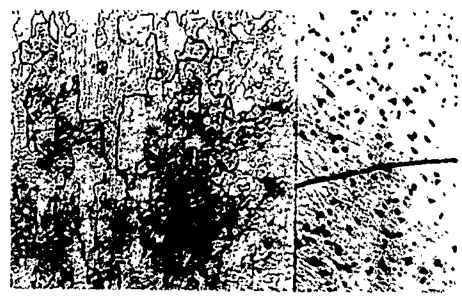


Microstructure -

As Brazed (2200°F/5 min.) Heat Treated (1800°F/65 hr.)



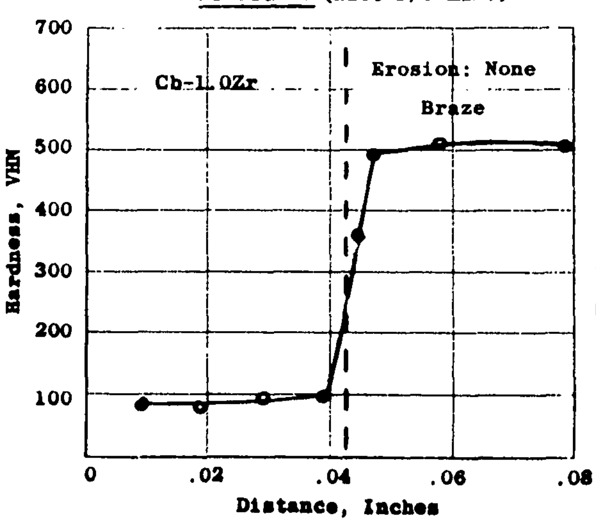
4296-1323 100X

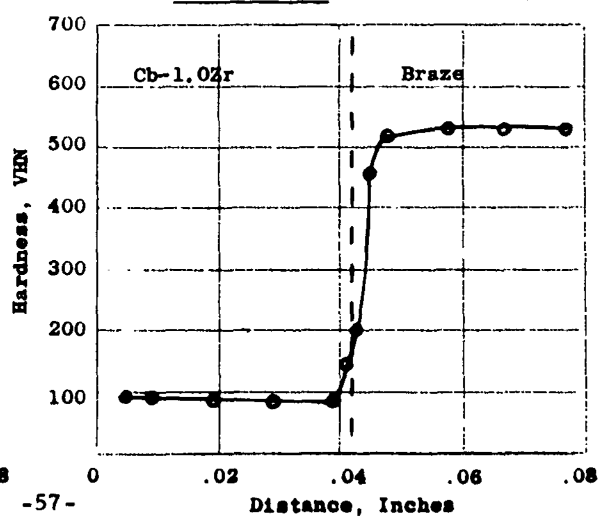


5396-2115 100X

Hardness Traverse -

As Brazed (2200°F/5 min.) Heat Treated (1800°F/65 hr.)





BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Cb-1.0Zr

Braze Alloy Designation	Nominal Composition	Melting Range °F Expected	Melting Range °F Actual	Hardness As Cast VHN	Ductility As Cast
AS505	Ti-10Cr	2910 2980	>2850 <2980	299	Ductile

Wettability -

Time: 5 min.
Temperature: 2850°F
Contact Angle: -
Mag: 1.5

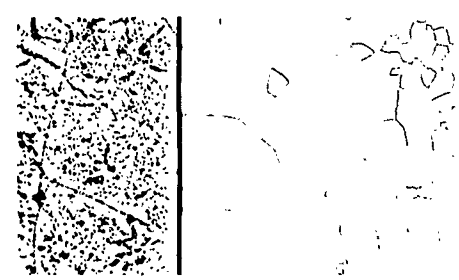
5 min.
2980°F
31°
1.5

Microstructure -

As Brazed (2980°F/5 min.)

4979-1951 100X

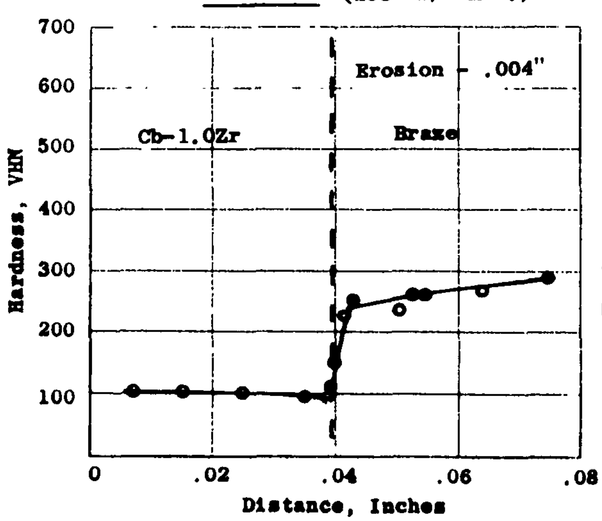
Heat Treated (2200°F/65 hrs



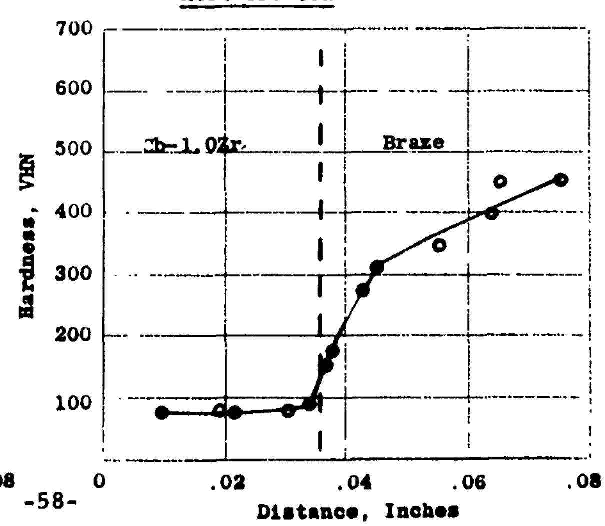
5410-2110 100X

Hardness Traverse -

As Brazed (2980°F/5 Min.)



Heat Treated (2200°F/65 Hrs.)



BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Cb-1.0Zr

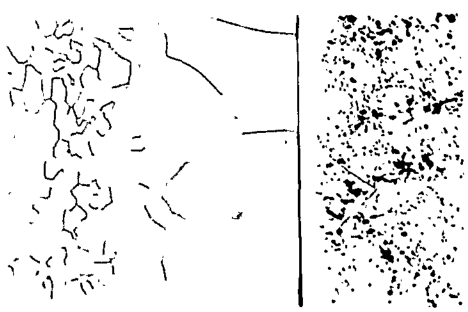
Braze Alloy Designation	Nominal Composition	Melting Range °F Expected	Melting Range °F Actual	Hardness As Cast VHN	Ductility As Cast
AS506A	Ti-20Cr	2710 2800	< 2725 < 2850	308	Ductile

Wettability -

Time :	5 min.	5 min.	5 min.
Temperature :	2725°F	2850°F	2980°F
Contact Angle :	-	-	30°-18°
Mag:	1.5	1.5	1.5

Microstructure -

As Brazed (2980°F/5 min.)



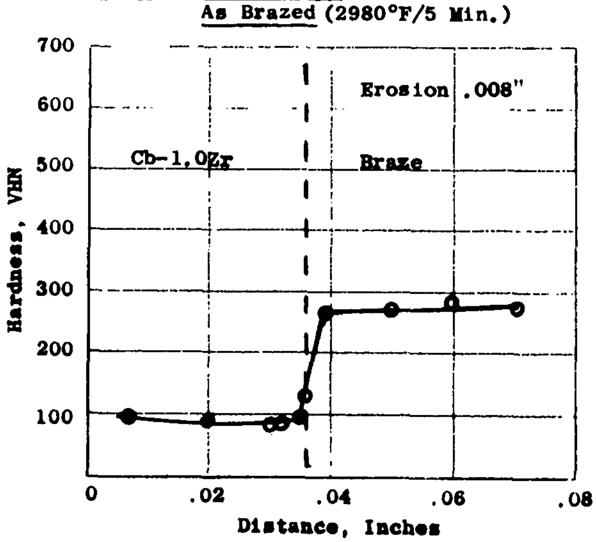
4981-1953 100X

Heat Treated (2200°F/65 hrs.)

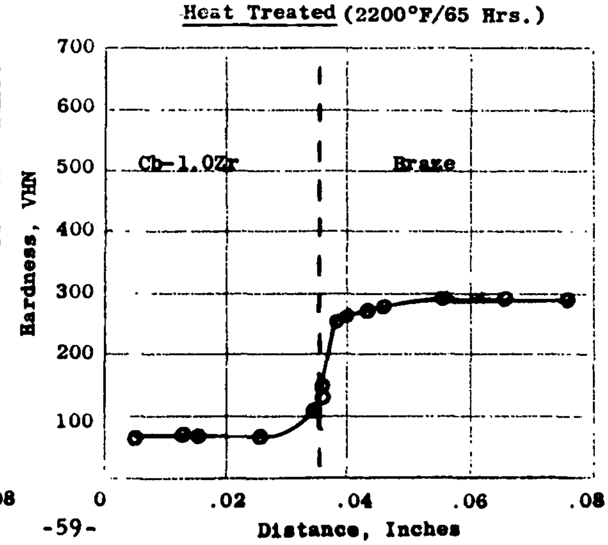
5411-2107 100X

Hardness Traverse -

As Brazed (2980°F/5 Min.)



Heat Treated (2200°F/65 Hrs.)



BRAZE ALLOY

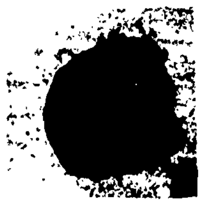
SUMMARY DATA SHEET

Base Metal: Cb-1.0Zr

Braze Alloy Designation	Nominal Composition	Melting Range °F Expected	Melting Range °F Actual	Hardness As Cast VHN	Ductility As Cast
AS511	Zr-11Al	2460	> 2400 < 2500	494	Brittle

Wettability -

Time:	5 min.	5 min.
Temperature:	2400°F	2500°F
Contact Angle:	-	9°
Mag:	1.6	1.1

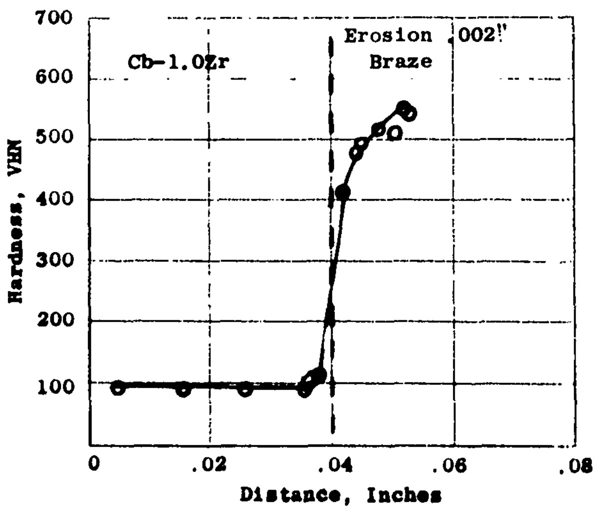


Microstructure -
As Brazed (2500°F/5 min.)

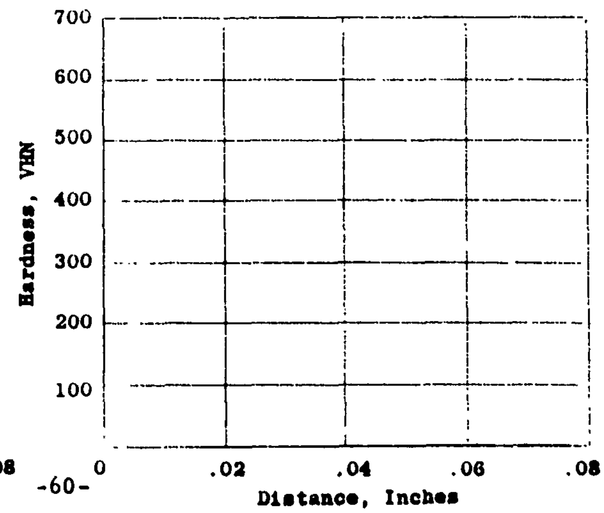
3492 - 2107 100X

Heat Treated (2200°F/65 hrs.)

Hardness Traverse -
As Brazed (2500°F/5 Min.)



Heat Treated



BRAZE ALLOY

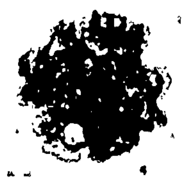
SUMMARY DATA SHEET

Base Metal: Cb-1.0Zr

Braze Alloy Designation	Nominal Composition	Melting Range °F Expected	Melting Range °F Actual	Hardness As Cast VHN	Ductility As Cast
AS535	Ti-13Fe-8Cr	-	< 2400 < 2500	412	Slightly Ductile

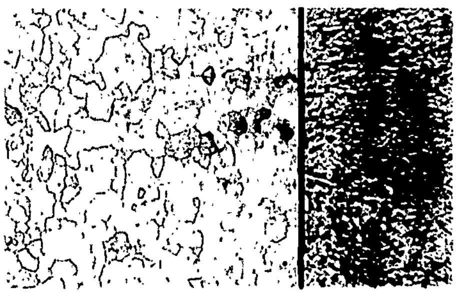
Wettability -

Time :	5 min.	5 min.
Temperature :	2400°F	2500°F
Contact Angle :	-	12°
Mag:	1.6	1.1



Microstructure -

As Brazed (2500°F/5 min.)



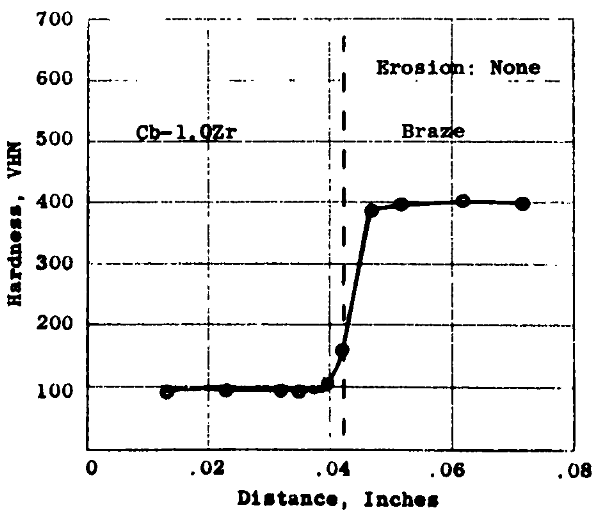
4268-1074 100X

Heat Treated (2200°F/65 hrs.)

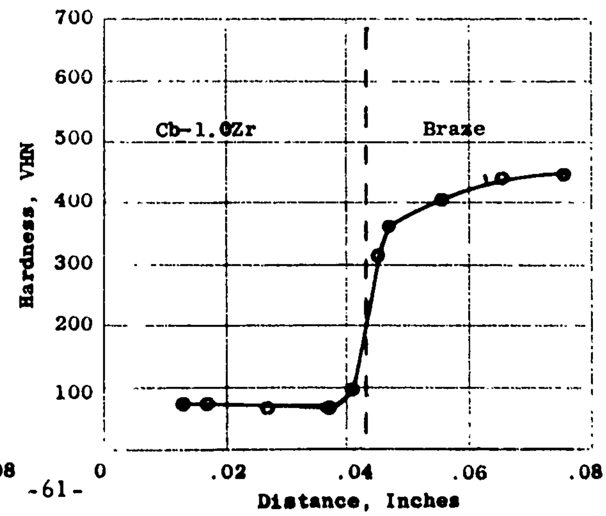
8413-2106 100X

Hardness Traverse -

As Brazed (2500°F/5 Min.)



Heat Treated (2200°F/65 Hrs.)



BRAZE ALLOY

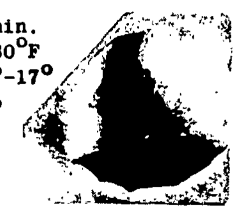
SUMMARY DATA SHEET

Base Metal: Cb-1.0Zr

Braze Alloy Designation	Nominal Composition	Melting Range °F Expected	Melting Range °F Actual	Hardness As Cast VHN	Ductility As Cast
AS536	Ti-6Fe-4Cr		< 2725 < 2850	325	Ductile

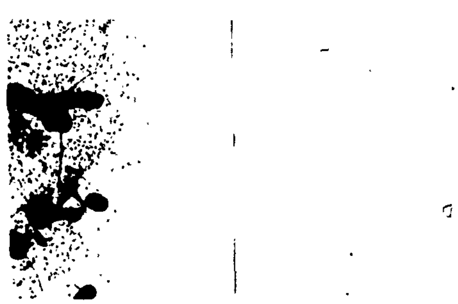
Wettability -

Time:	5 min.	5 min.	5 min.
Temperature:	2725°F	2850°F	2980°F
Contact Angle:	-	28°	28°-17°
Mag:	1.5	1.5	1.5



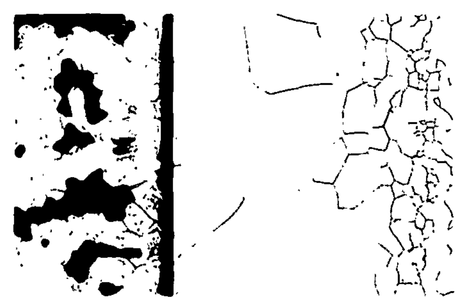
Microstructure -

As Brazed (2980°F/5 min.)



4987-1960 100X

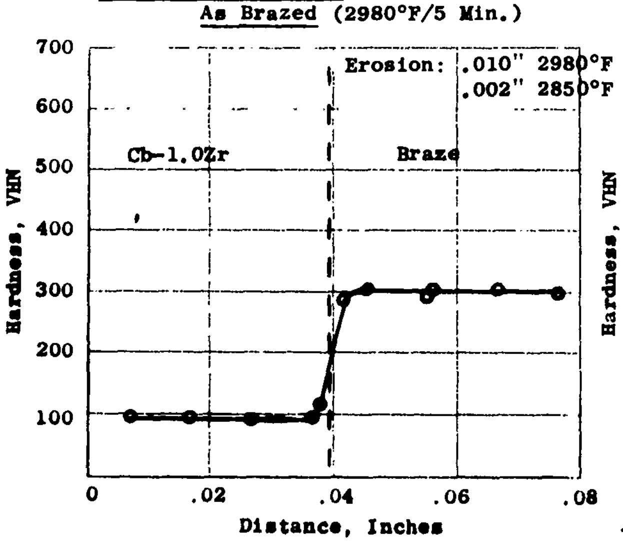
Heat Treated (2200°F/65 hrs.)



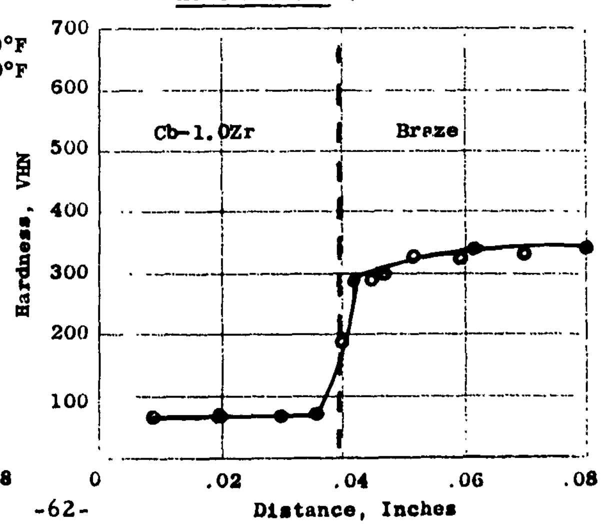
5414-2108 100X

Hardness Traverse -

As Brazed (2980°F/5 Min.)



Heat Treated (2200°F/65 Hrs.)



BRAZE ALLOY

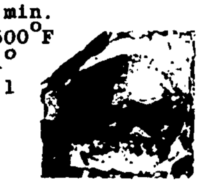
SUMMARY DATA SHEET

Base Metal: Cb-1.0Zr

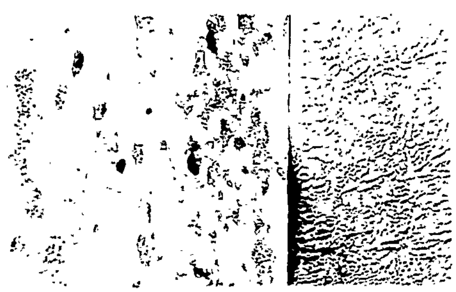
Braze Alloy Designation	Nominal Composition	Melting Range °F Expected	Melting Range °F Actual	Hardness As Cast VHN	Ductility As Cast
AS537	Zr-28V-16Ti	-	> 2100 < 2200	391	Ductile

Wettability -

Time :	5 min.	5 min.	5 min.
Temperature :	2200°F	2400°F	2500°F
Contact Angle :	29°		11°
Mag:	1.8	1.6	1.1



Microstructure -
As Brazed (2300°F/5 min.)

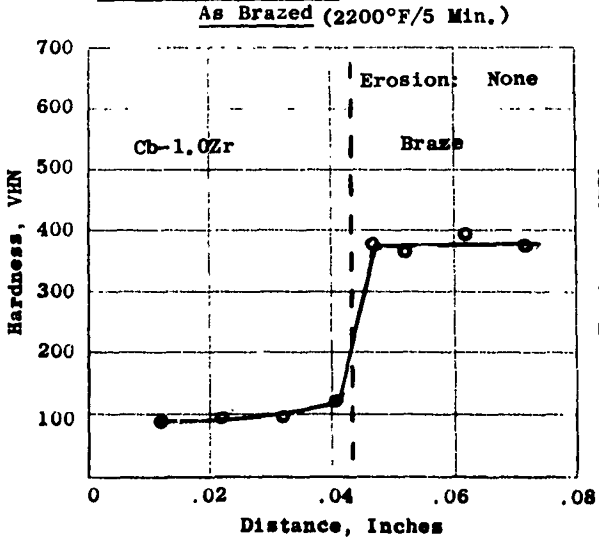


4395-1327 100X

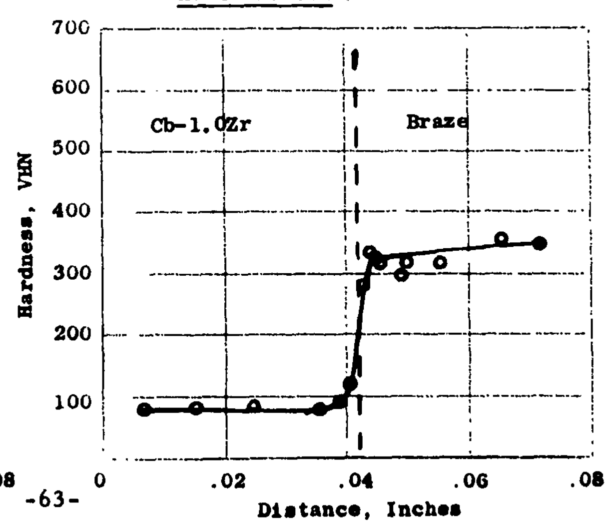
Brazed 2200°F
Heat Treated (1800°F/65 hr.)

5397-2104 100X

Hardness Traverse -
As Brazed (2200°F/5 Min.)



Heat Treated (1800°F/65 Hrs.)



X

BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: F-48

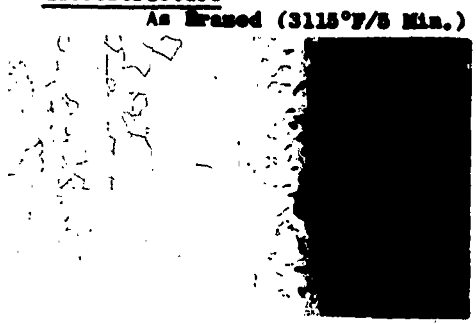
Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-500-2	100 Ti	3128 3128	3105 3115 (AS-500-1)	130	Ductile

Wettability -

Time:	5 Min.
Temperature:	3115°F
Contact Angle:	41°
Mag:	---

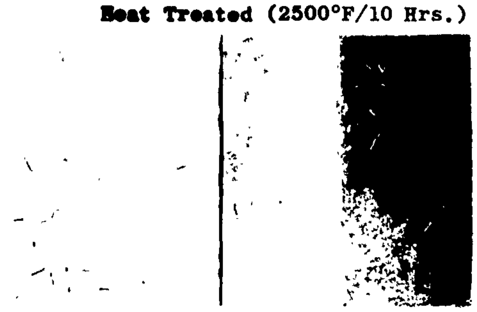
Microstructure -

As Brazed (3115°F/5 Min.)



5427-2094 100X

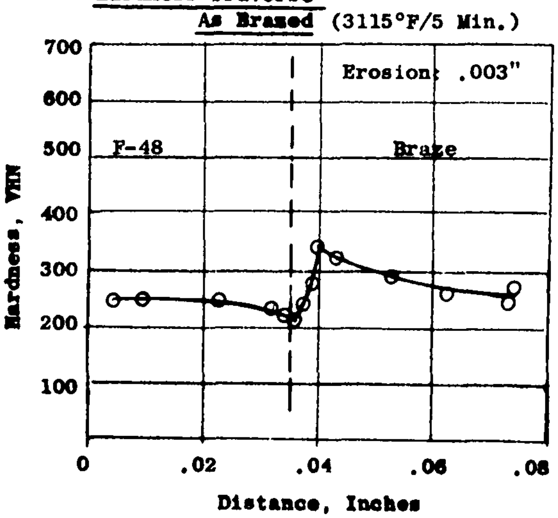
Heat Treated (2500°F/10 Hrs.)



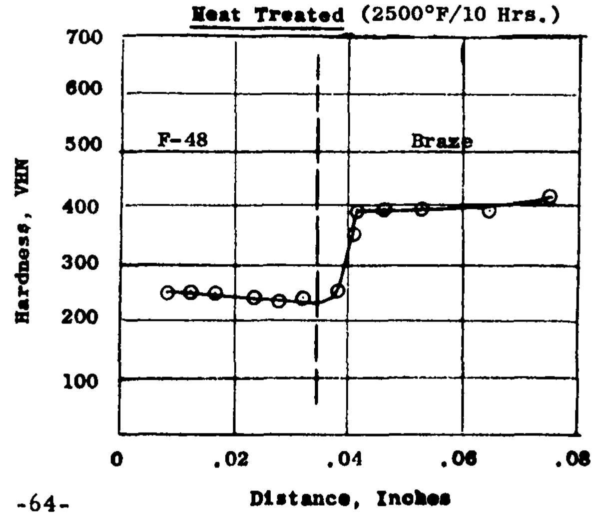
5300-2096 100X

Hardness Traverse -

As Brazed (3115°F/5 Min.)



Heat Treated (2500°F/10 Hrs.)



BRAZE ALLOY

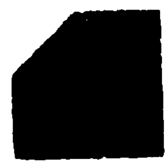
SUMMARY DATA SHEET

Base Metal: F-48

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-501	Ti-30V	2950 2950	2970 2970	229	Ductile

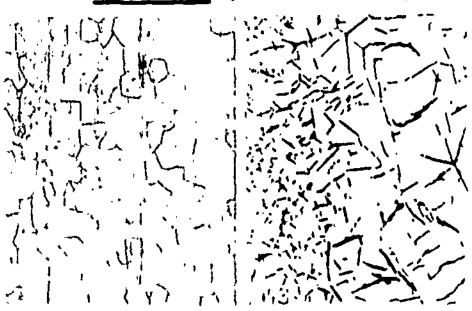
Wettability -

Time:	5 Min.	5 Min.	
Temperature:	2970°F	3050°F	
Contact Angle:	33°	---	
Mag:	1.2	1.2	

Microstructure -

As Brazed (2970°F/5 Min.)



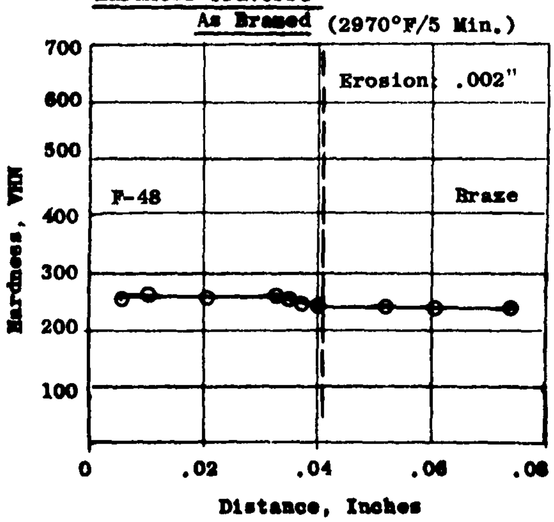
3280-218 100X

Heat Treated (2500°F/10 Hrs.)

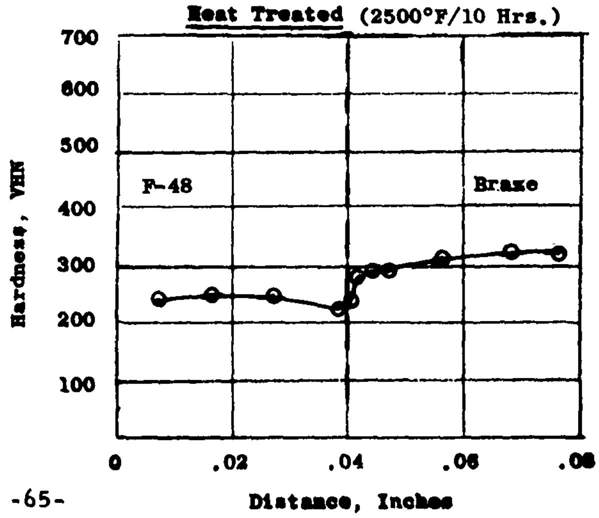
5400-2092 100X

Hardness Traverse -

As Brazed (2970°F/5 Min.)



Heat Treated (2500°F/10 Hrs.)



BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: F-48

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Actual	Hardness As Cast VHN	Ductility As Cast
AS-508	100 Zr	3366	3320	173	Ductile
		3366	3330		

Wettability -

Time: 5 Min.
Temperature: 3330°F
Contact Angle: 20°
Mag: --

Microstructure -

As Brazed (3330°F/7 Min.)

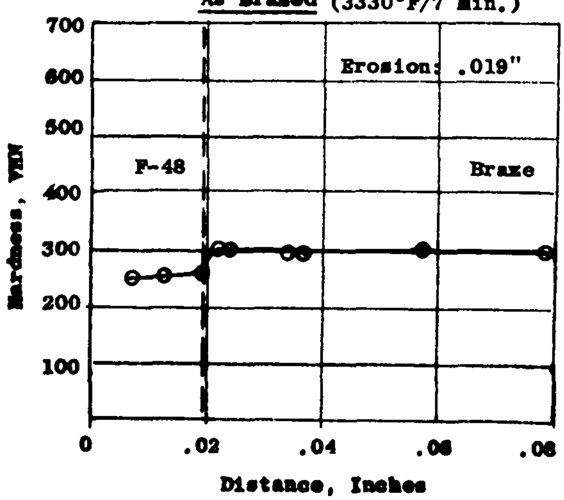
3348-12427 100X

Heat Treated (2500°F/10 Hrs.)

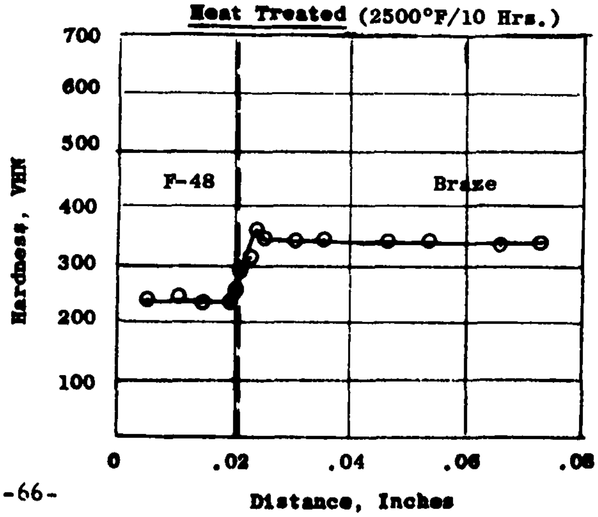
5402-2101 100X

Hardness Traverse -

As Brazed (3330°F/7 Min.)



Heat Treated (2500°F/10 Hrs.)



BRAZE ALLOY

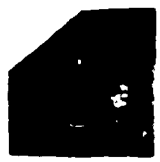
SUMMARY DATA SHEET

Base Metal: F-48

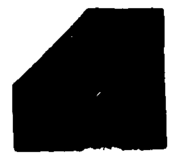
Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-509	Zr-22Cb	3164	3150	223	Ductile
		3164	3190		

Wettability -

Time: 5 Min.
Temperature: 3150°F
Contact Angle: --
Mag: 1.2



5 Min.
3190°F
27°
1.2

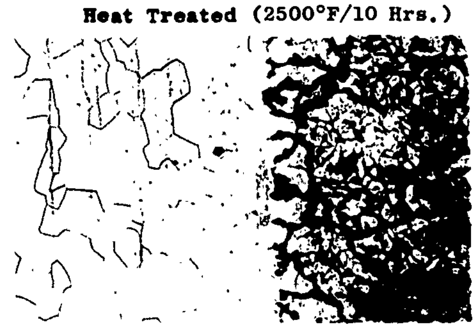


Microstructure -

As Brazed (3190°F/5 Min.)

3438-216 100X

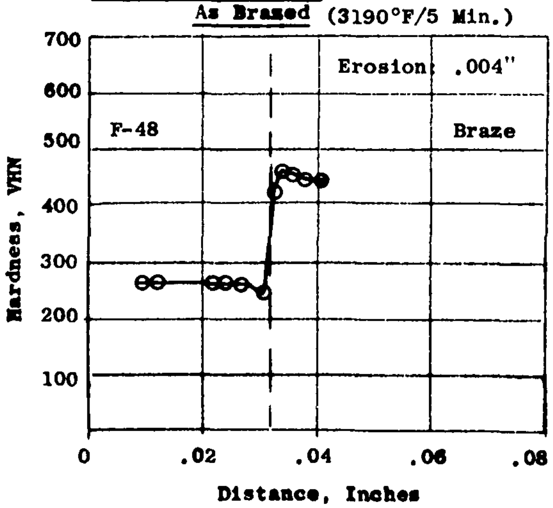
Heat Treated (2500°F/10 Hrs.)



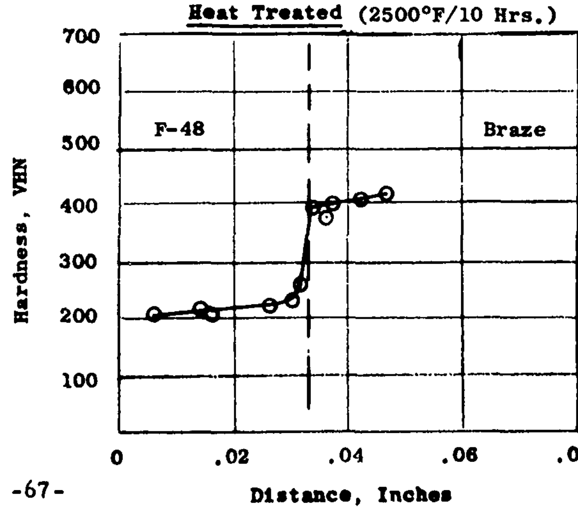
5405-2100 100X

Hardness Traverse -

As Brazed (3190°F/5 Min.)



Heat Treated (2500°F/10 Hrs.)



BRAZE ALLOY

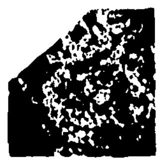
SUMMARY DATA SHEET

Base Metal: F-48

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-513	V-20Ti	3180 3280	< 3150 3190	231	Ductile

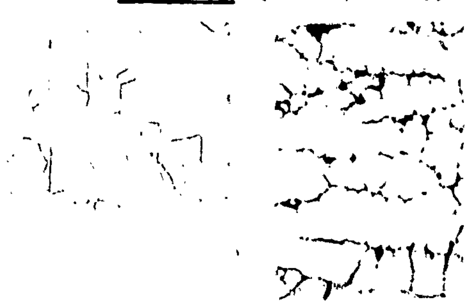
Wettability -

Time:	5 Min.		5 Min.
Temperature:	3150°F		3190°F
Contact Angle:	---		8°
Mag:	1.2		1.2



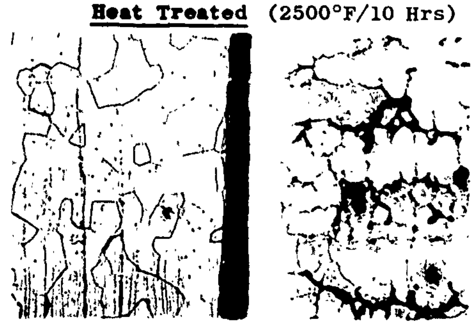
Microstructure -

As Brazed (3190°F/5 Min.)



4344-1468 100X

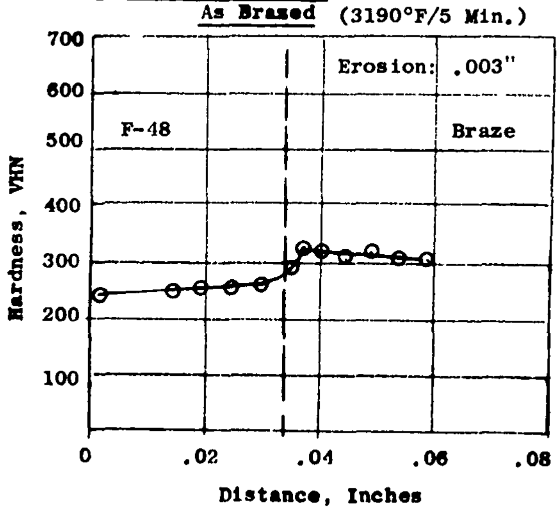
Heat Treated (2500°F/10 Hrs)



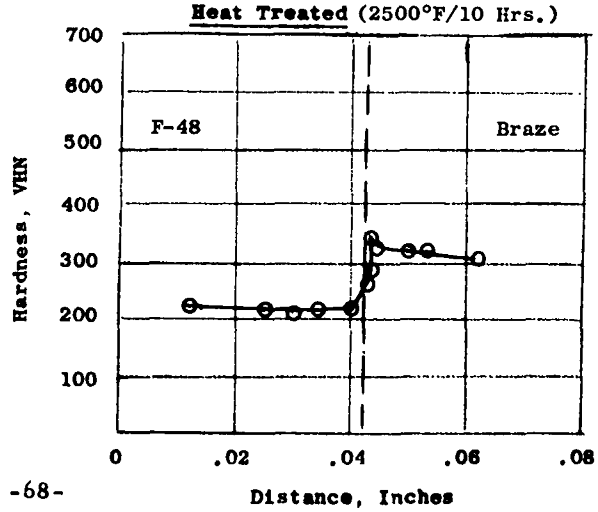
5403-2097 100X

Hardness Traverse -

As Brazed (3190°F/5 Min.)



Heat Treated (2500°F/10 Hrs.)



BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: F-48

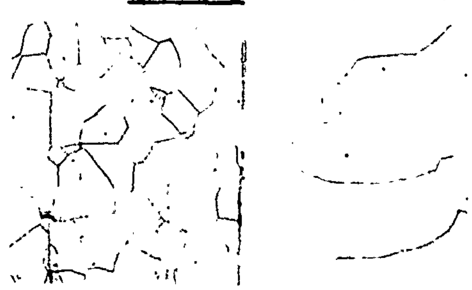
Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-514	V-35Cb	3290	3300	332	Ductile
		3290	3400		

Wettability -

Time: 5 Min.
Temperature: 3400°F
Contact Angle: 12°
Mag: 1.2

Microstructure -

As Brazed (3400°F/5 Min.)



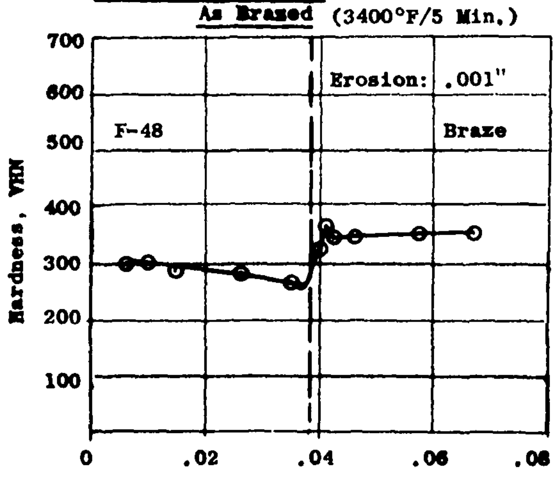
4643-1466 100X

Heat Treated (2500°F/10 Hrs.)

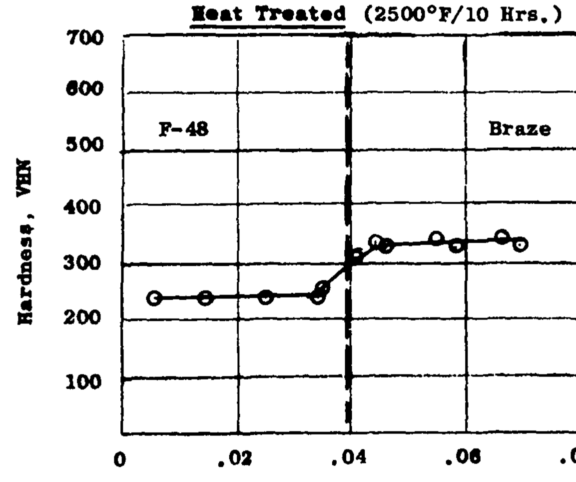
5404-2098 100X

Hardness Traverse -

As Brazed (3400°F/5 Min.)



Heat Treated (2500°F/10 Hrs.)



BRAZE ALLOY

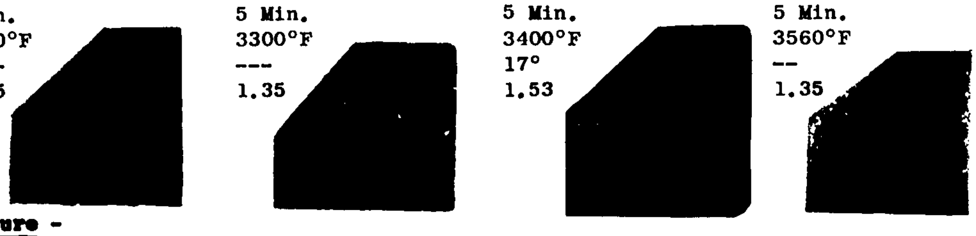
SUMMARY DATA SHEET

Base Metal: F-48

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Actual	Hardness As Cast VHN	Ductility As Cast
AS-538	Zr-34Ta	--	3000 3400	406	Brittle

Wettability -

Time:	5 Min.	5 Min.	5 Min.	5 Min.
Temperature:	3000°F	3300°F	3400°F	3560°F
Contact Angle:	--	---	17°	--
Mag:	1.35	1.35	1.53	1.35



Microstructure -

As Brazed (3400°F/5 Min.)

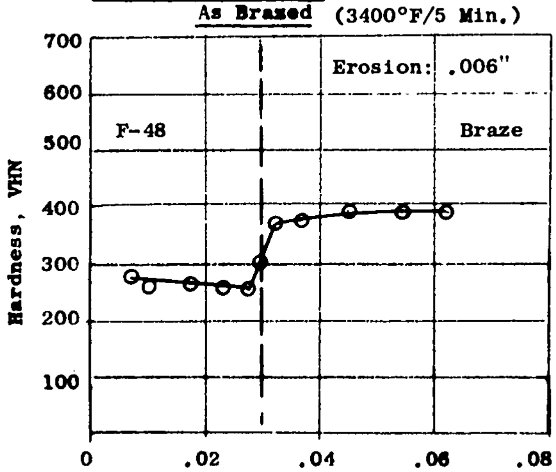
4949-1963 100X

Heat Treated (2500°F/10 Hrs.)

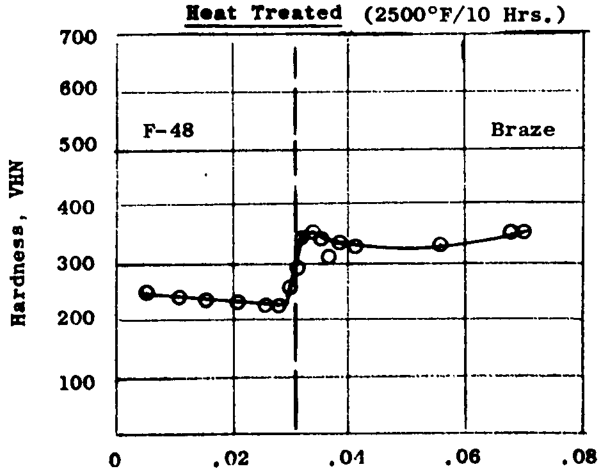
5406-2091 100X

Hardness Traverse -

As Brazed (3400°F/5 Min.)



Heat Treated (2500°F/10 Hrs.)



APPENDIX B

BRAZING ALLOYS FOR TUNGSTEN

SUMMARY DATA SHEETS

BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

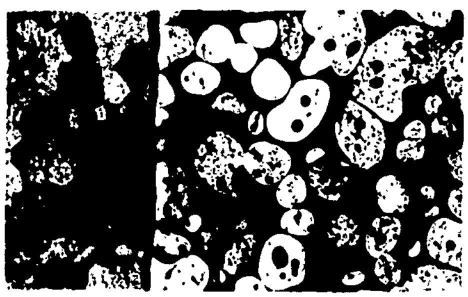
Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Actual	Hardness As Cast VHN	Ductility As Cast
AS-516	Cb-1.0B	--	>3800	232	Ductile
		--	>4000		

Wettability -

Time: 5 Mins.
Temperature: 4000°F
Contact Angle: --
Mag: 1.7

Note: Crack along Braze/W interface.

Microstructure -
As Brazed (4000°F/5 Min.)

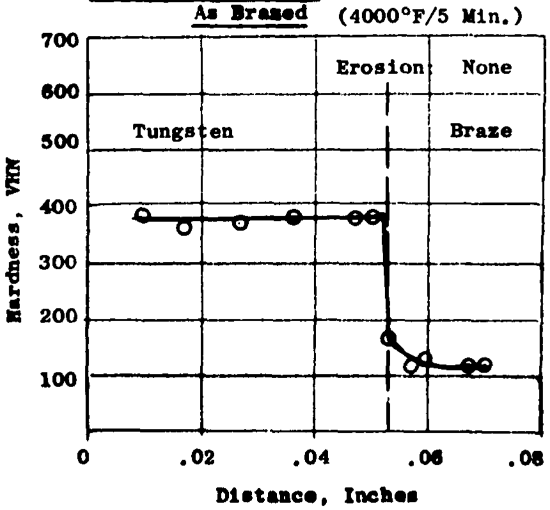


6033-3154 100X

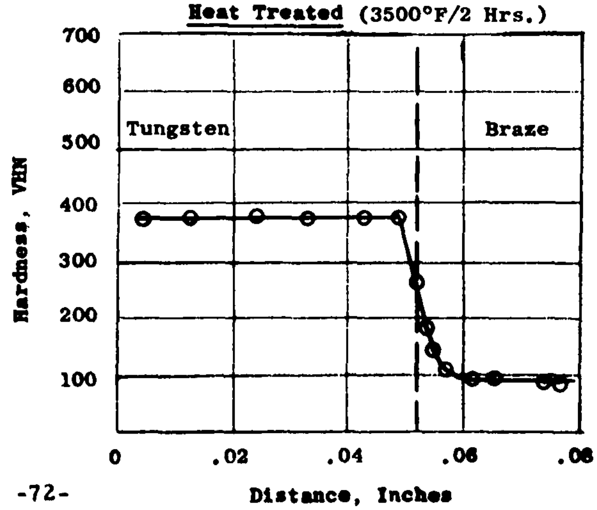
Heat Treated (3500°F/2 Hrs.)

6297-3156 100X

Hardness Traverse -
As Brazed (4000°F/5 Min.)



Heat Treated (3500°F/2 Hrs.)



BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-517	Cb-2.2B	2930	>3800 <4000	301 (As cast) 315 (H.T.)	Ductile

Homogenized 2400°F/16 Hrs. Prior to Brazing

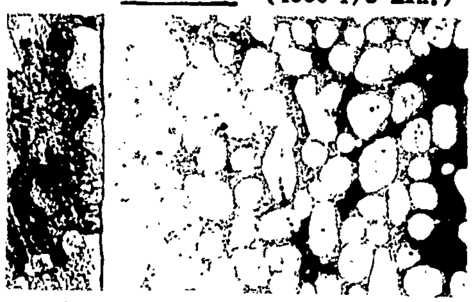
Wettability -

No Homogenization

Time:	5 Min.	5 Min.	5 Min.
Temperature:	3600°F	3700°F	4000°F
Contact Angle:	-	-	3°
Mag:	1.45	1.45	1.7

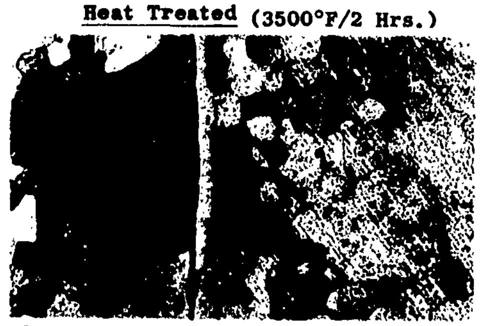
Microstructure -

As Brazed (4000°F/5 Min.)



6036-3157 100X

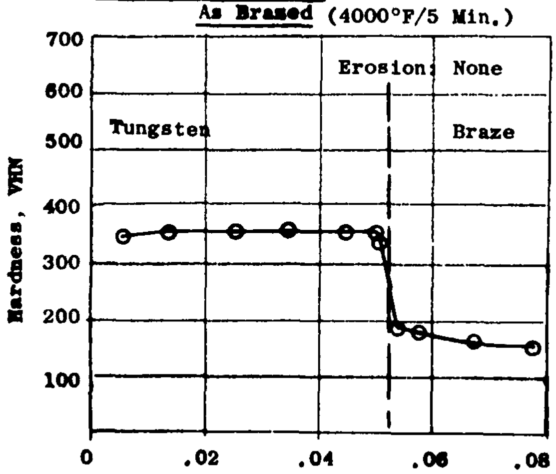
Heat Treated (3500°F/2 Hrs.)



6298-3159 100X

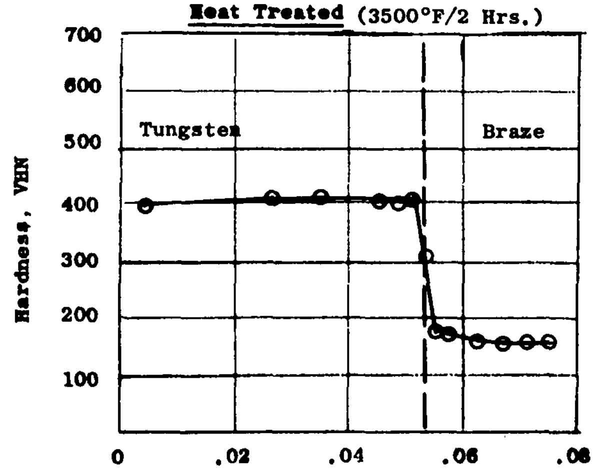
Hardness Traverse -

As Brazed (4000°F/5 Min.)



Distance, Inches

Heat Treated (3500°F/2 Hrs.)



Distance, Inches

BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

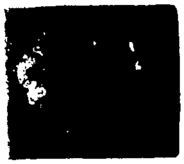
Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-539	Cb-3.0B	--	> 3800 < 4000	323 (As cast) 258 (H.T.)	Slightly Ductile

Homogenized 2400°F/16 Hrs. prior to brazing.

Wettability -

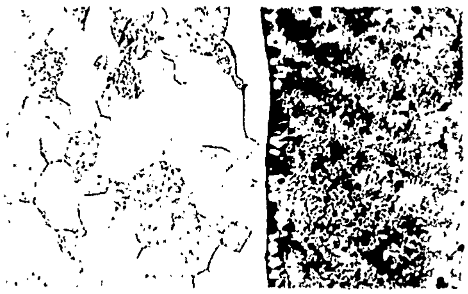
No homogenization

Time:	5 Min.	5 Min.		5 Min.	
Temperature:	3700°F	3800°F		4000°F	
Contact Angle:	--	--		6°	
Mag:	1.45	1.45		1.7	



Microstructure -

As Brazed (4000°F/5 Min.)



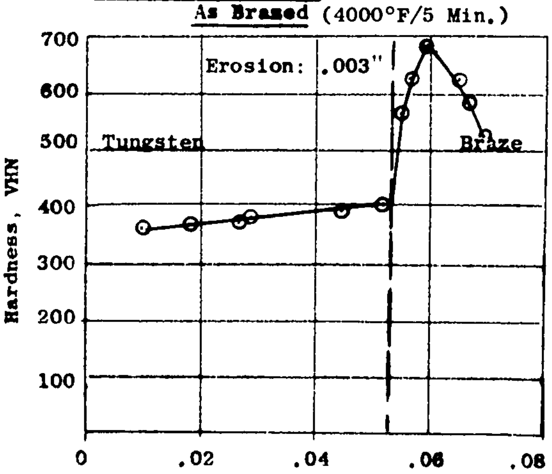
6037-3160 100X

Heat Treated (3500°F/2 Hrs.)

6299-3162 100X

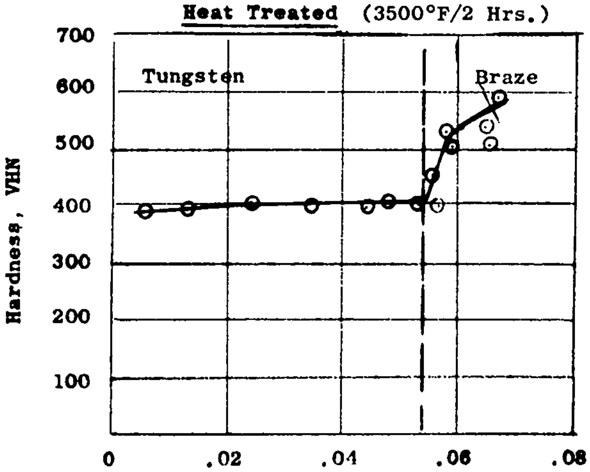
Hardness Traverse -

As Brazed (4000°F/5 Min.)



Distance, Inches

Heat Treated (3500°F/2 Hrs.)



Distance, Inches

BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

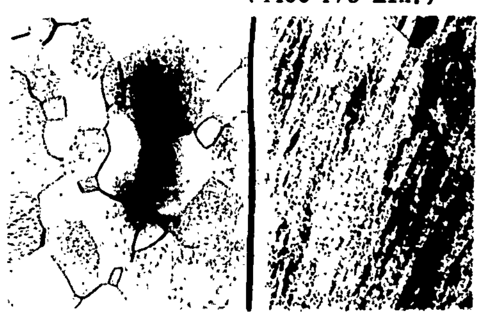
Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-518	Cb-10Ti	4020 4340	> 4300 4400	163	Ductile

Wettability -

Time:	5 Min.		5 Min.
Temperature:	4300°F		4400°F.
Contact Angle:	--		12°
Mag:	1.6		1.6

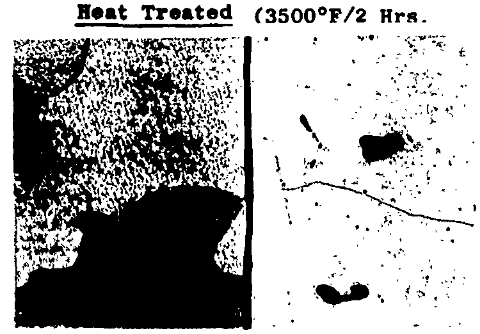
Microstructure -

As Brazed (4400°F/5 Min.)



8843-3138 **100X**

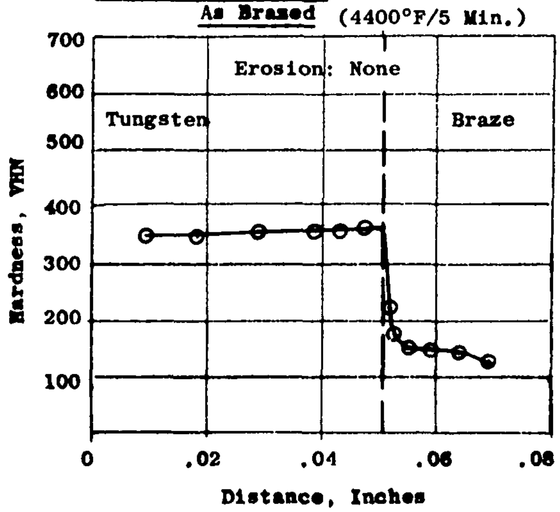
Heat Treated (3500°F/2 Hrs.



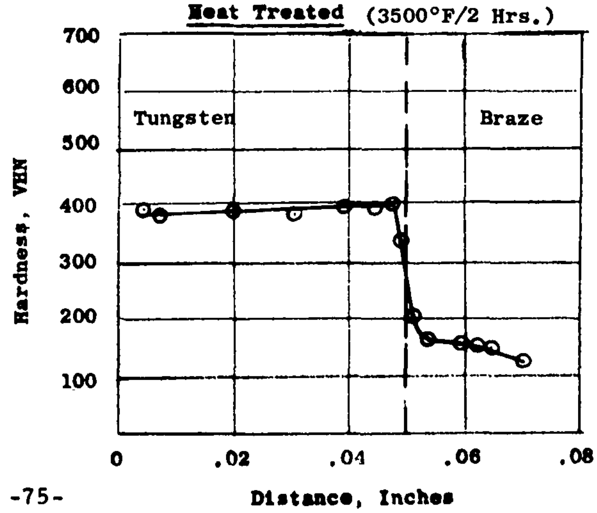
6289-3140 100X

Hardness Traverse -

As Brazed (4400°F/5 Min.)



Heat Treated (3500°F/2 Hrs.)



BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-519	Cb-20Ti	3790 4260	4000 4100	192	Ductile

Wettability -

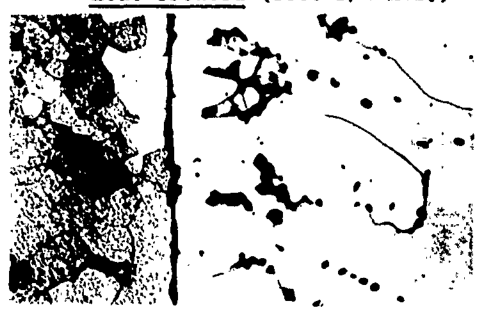
Time:	5 Min.		5 Min.
Temperature:	4000°F		4100°F
Contact Angle:	--		15°
Mag:	1.55		1.55

Microstructure -

As Brazed (4100°F/5 Min.)

4943-1970 100X

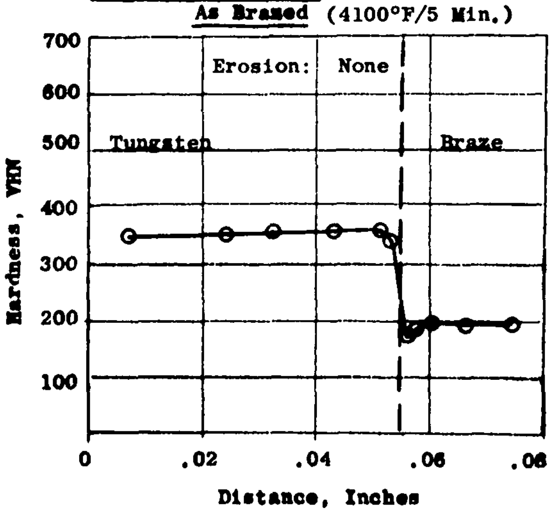
Heat Treated (3500°F/2 Hrs.)



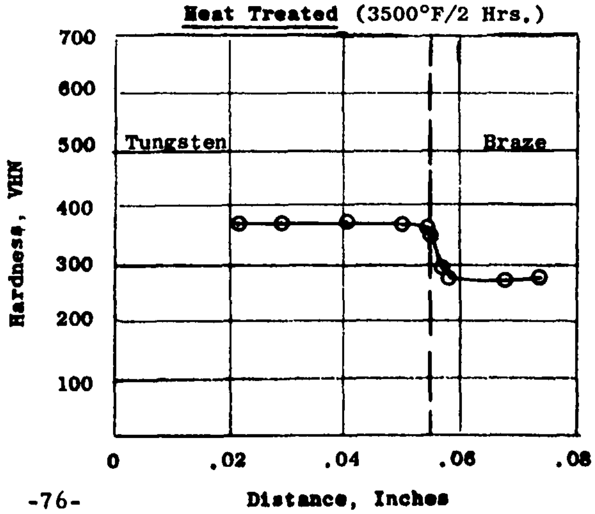
6291-3142 100X

Hardness Traverse -

As Brazed (4100°F/5 Min.)



Heat Treated (3500°F/2 Hrs.)



BRAZE ALLOY

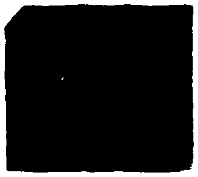
SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-520	Cb-10V	4060 4160	4100 4400	263	Ductile

Wettability -

Time:	5 Min.	5 Min.	5 Min.
Temperature:	4100°F	4300°F	4400°F
Contact Angle:	--	--	13°
Mag:	1.57	1.57	1.57



Microstructure -

As Brazed (4400°F/5 Min.)

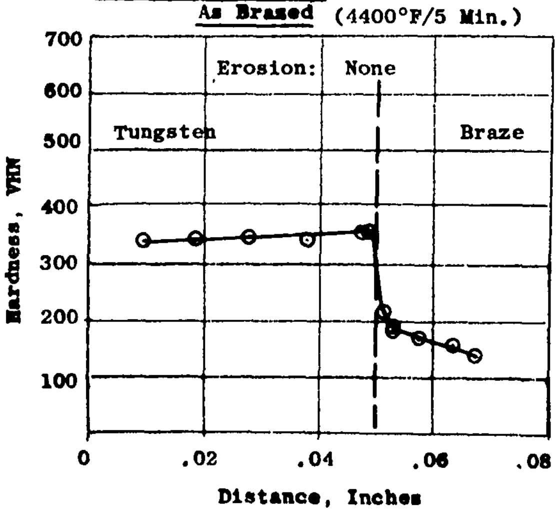
5245-3143 100X

Heat Treated (3500°F/2 Hrs.)

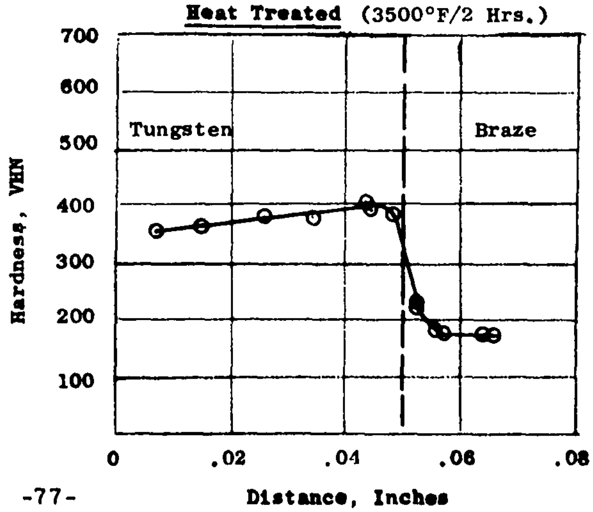
6292-3145 100X

Hardness Traverse -

As Brazed (4400°F/5 Min.)



Heat Treated (3500°F/2 Hrs.)



BRAZE ALLOY

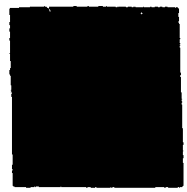
SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-521	Cb-20V	3760 3880	4000 4250	318	Ductile

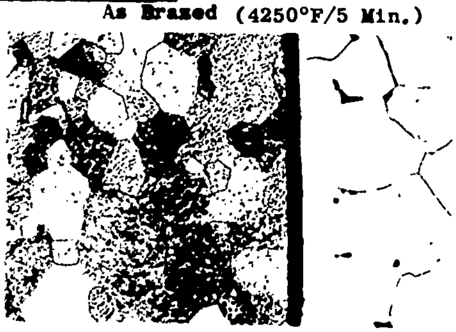
Wettability -

Time:	5 Min.	5 Min.	5 Min.
Temperature:	4000°F	4100°F	4250°F
Contact Angle:	--	--	15°
Mag:	1.55	1.55	1.55



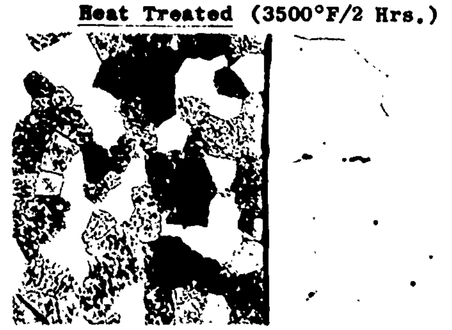
Microstructure -

As Brazed (4250°F/5 Min.)



4939-1967 100X

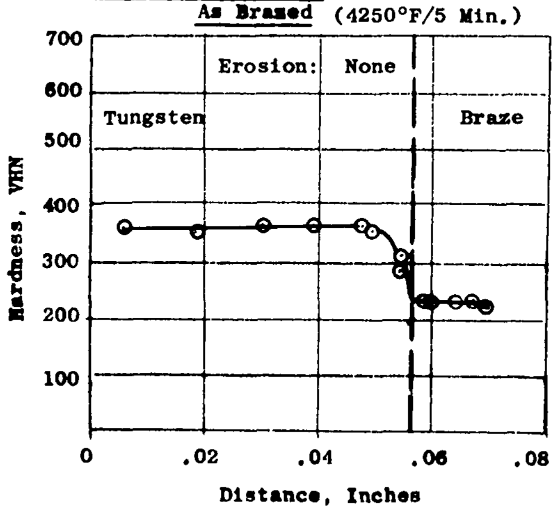
Heat Treated (3500°F/2 Hrs.)



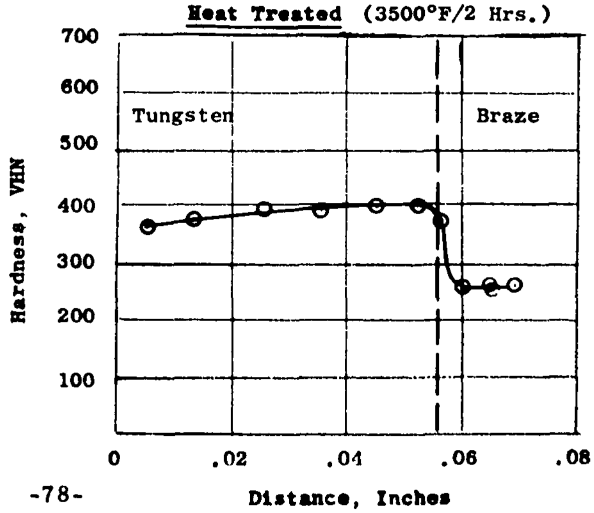
6293-3147 100X

Hardness Traverse -

As Brazed (4250°F/5 Min.)



Heat Treated (3500°F/2 Hrs.)



BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

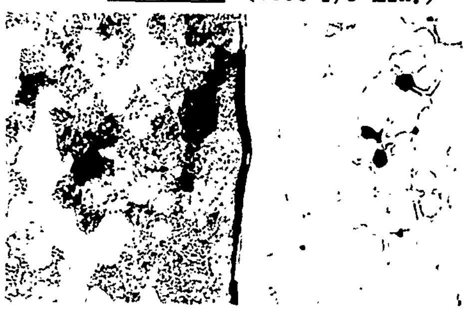
Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-522	Cb-15Ni	4000 ?	<4000	597	Brittle

Wettability -

Time: 5 Min.
Temperature: 4000°F
Contact Angle: --
Mag: 1.55

Note: Specimen broke during removal from furnace.

Microstructure -
As Brazed (4000°F/5 Min.)

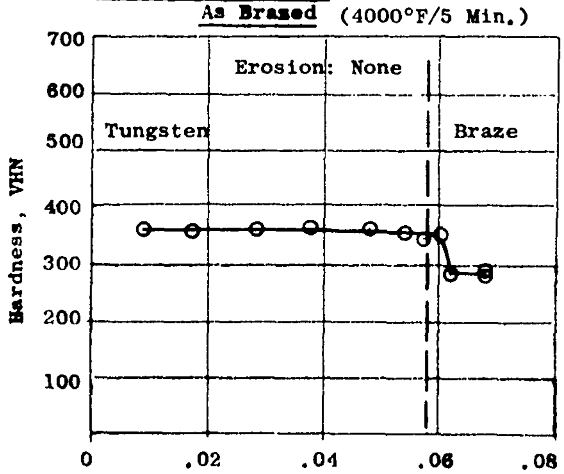


4937-1966 **100X**

Heat Treated (3500°F/2 Hrs.)

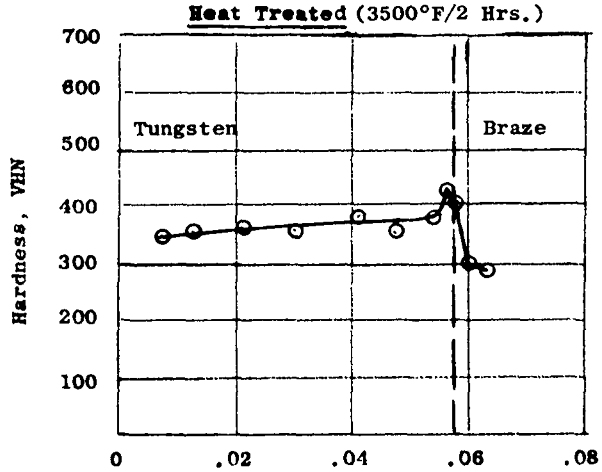
6294-3148 100X

Hardness Traverse -
As Brazed (4000°F/5 Min.)



Distance, Inches

Heat Treated (3500°F/2 Hrs.)



Distance, Inches

BRAZE ALLOY

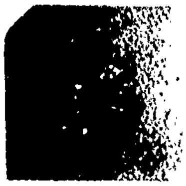
SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-523	Cb-5Ni	?	4100	247	Slightly Ductile
		?	4400		

Wettability -

Time:	5 Min.	5 Min.
Temperature:	4100°F	4400°F
Contact Angle:	--	16°
Mag:	1.55	1.55

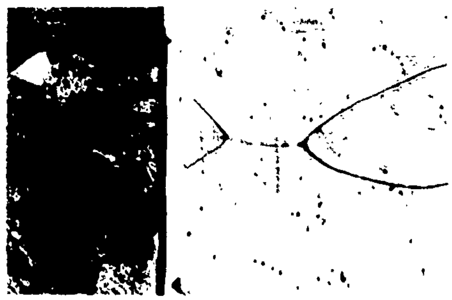


Microstructure -

As Brazed (4400°F/5 Min.)

5247-3149 100X

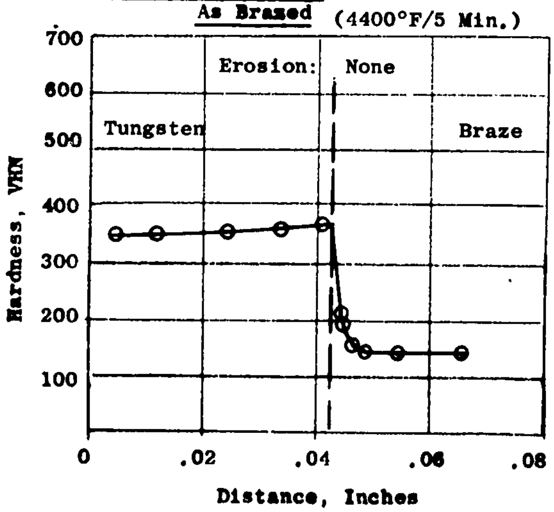
Heat Treated (3500°F/2 Hrs.)



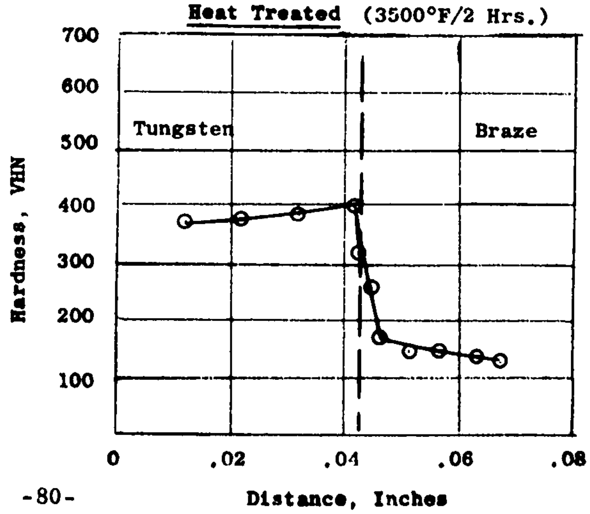
6295-3151 100X

Hardness Traverse -

As Brazed (4400°F/5 Min.)



Heat Treated (3500°F/2 Hrs.)



BRAZE ALLOY

SUMMARY DATA SHEET

Base Metal: Unalloyed Tungsten

Braze Alloy Designation	Nominal Composition	Melting Range, °F Expected	Melting Range, °F Actual	Hardness As Cast VHN	Ductility As Cast
AS-529	Ta-25V	3810 ?	< 3950 4250	393	Ductile

Wettability -

Time:	5 Min.	5 Min.	5 Min.
Temperature:	3950°F	4150°F	4250°F
Contact Angle:	--	--	51°
Mag:	1.53	1.53	1.53



Microstructure -

As Brazed (4250°F/5 Min.)

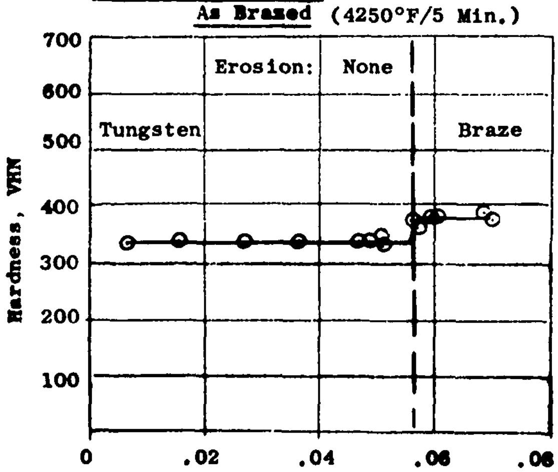
4935-1965 100X

Heat Treated (3500°F/2 Hrs.)

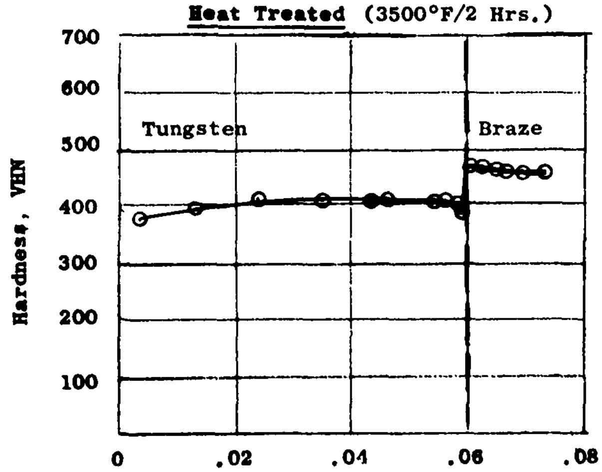
6296-3153 100X

Hardness Traverse -

As Brazed (4250°F/5 Min.)



Heat Treated (3500°F/2 Hrs.)



GENERAL ELECTRIC COMPANY, Evendale, Ohio, ALLOY SYSTEMS FOR BRAZING OF COLUMBIUM AND TUNGSTEN, by W. R. Young, January 1962, 81p incl. illus., tables. (Task 73512) (ASD TR 61-592) (Contract AF 33(616)-7484)
Unclassified Report

Brazing alloy systems based on Cb, Ta, V, Ti, and Zr were evaluated for melting range, wettability and flow, and metallurgical compatibility with columbium alloys and unalloyed tungsten. Joint shear strength, effect on base alloy transition temperature, and compatibility with protective coatings were determined for selected alloys.

(over)

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